RECOMMENDED GUIDELINES FOR STATION POSITIONING IN PUGET SOUND

Prepared for:

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LIST OF ACRONYMS

ADCP	Acoustic Doppler Current Profiler
COP	Circle-Of-Position
CTD	Conductivity, Temperature, Depth (Instrument)
DGPS	Differential Global Positioning System
DMMO	Dredged Material Management Office
DMMP	Dredged Material Management Program
DOD	Department of Defense
DOE	Washington State Department of Ecology
DOT	Department of Transportation
EDMI or **EDM**	Electronic Distance Measuring Instrument
EPA	United States Environmental Protection Agency
FGDC	Federal Geographic Data Committee
GIS	Geographic Information System
GPS	Global Positioning System
LOP	Line-Of-Position
LORAN-C	LOng RAnge Navigation
NAD 27 or **NAD 83**	North American Datum of 1927 (or of 1983)
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NSSDA	National Standard for Spatial Data Accuracy
OSHA	Occupational Safety and Health Administration
PDOP	Position Dilution of Precision
PPS	Precise Positioning Service
PSAMP	Puget Sound Ambient Monitoring Program
PSDDA	Puget Sound Dredged Disposal Analysis
PSEP	Puget Sound Estuary Program
PSWQAT	Puget Sound Water Quality Action Team
PSWQA	Puget Sound Water Quality Authority
SA	Selective Availability
SAP	Sampling and Analysis Plan
SPS	Standard Positioning Service
USCG	U.S. Coast Guard
USGS	U.S. Geological Survey
UTC	Universal Time Coordinated
VHF	Very High Frequency
WGS 84	World Geodetic System 1984

DEFINITIONS

The following terms are defined only to the extent of how they are used in this document. It is understood that fuller definitions may exist elsewhere in some cases.

absolute (predictable) accuracy - the positional accuracy with respect to geographic or geodetic coordinates.
backsight - a visual target of known position that is used to zero in the azimuth scale of a theodolite or Total Station.
baseline - a line of known length or position connecting two range and/or azimuth measuring devices.
binnacle - the primary ship's compass, typically mounted in the wheelhouse.
circle-of-position (COP) - a curved line-of-position (or arc) with the radius being equal to a known distance; a hyperbolic line-of-position (Harmon, 1994).
datum - a mathematical model of the Earth relative to a planetary reference point where the Earth's surface is viewed according to the actual terrain, or as a representation (geoid) over which gravity is constant (Trimble, 1996a).
ellipsoid - "the 3D mathematical figure formed by rotating an ellipse around its minor axis" (Trimble, 1996a).
fix - the best estimate of the position of a vessel (Harmon, 1994).
geoid - "a representation of the surface of the Earth over which the Earth's gravity is constant." (Trimble, 1996a)
inertial navigation - an autonomous system for tracking positions in three dimensions by monitoring vehicle movement through the use of gyroscope-stabilized accelerometers.
hyperbolic mode - a mode of operation whereby an instrument calculates distances based on the phase difference between signals arriving from two or more shore-based transmitters.
line-of-position (LOP) - a straight line (or track) representing possible positions of a vessel (Harmon, 1994).
omnidirectional - a non-directional antenna that transmits 360^o.
radial error - the area of probable vessel position that can be resolved by a specific navigational method.
range-range mode - a mode of operation whereby an instrument calculates distances based on measured time intervals between outgoing and incoming signals.
relative accuracy - the accuracy to which one navigator can locate himself relative to a second navigator using the same positioning methodology (ODIN, 1997).
repeatable accuracy - the accuracy by which a navigator can re-acquire a position whose initial coordinates were established using the same positioning methodology. [Repeatable and relative accuracies are often used interchangeably in many documents.]
reference point - a point of reference, the geodetic coordinates of which are known, that can be used to help establish a positional fix.
scope - the ratio of the anchor line length to the vertical distance between the anchoring point and the bottom.
transceiver - a device capable of both transmitting and receiving acoustical signals.
transducer - a device that converts an electrical signal into an acoustical pulse which is then transmitted into the surrounding water.
transponder - a device that, upon receiving a designated signal, replies by transmitting its own signal.
triangulate - to determine a vessel's position at the point of intersection of two or more LOPs, each having been created from either (1) an angle swung between a known baseline and a bearing to the vessel, or (2) the vessel's bearing to a known fixed point.
trilaterate - to determine a vessel's position at the point of intersection of two or more COPs with the radius of each arc representing a measured distance to a known fixed point.
vessel - broadly defined as any floating platform from which marine activities take place. Where positioning methods are concerned, this term can also be interpreted to include reference to aircraft in most cases.

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e. Provided written and/or verbal comments.

1. INTRODUCTION

This document presents recommended guidelines for vessel navigation and station positioning when participating in marine environmental studies in support of various Puget Sound monitoring and regulatory programs. The environs where these positioning methodologies have been used successfully are the intertidal, estuarine, nearshore, and offshore areas within the Puget Sound region.

The purpose of developing these station positioning guidelines is to encourage the use of standardized methods for determining vessel and sampling station positions, and for recording the subsequent coordinate data in a consistent and uniform way. The use of standardized navigational methodologies should aid in producing more comparable data resulting from ongoing and future studies performed in the Puget Sound region.

This document attempts to provide a cohesive, performance-related, and practical reference that describes proven techniques for establishing sampling points and vessel positions through the use of standard navigational and surveying instrumentation. It is not all-inclusive, nor is it intended to be an authoritative discourse on professional marine and land surveying techniques and practices.

The guidelines described herein have been generalized to the extent where they could be used for all types of marine environmental activities rather than just ‘sampling operations’. Likewise, the term ‘vessel’ also has broader meaning. Where this term is used, the implication is that the associated positioning methodology will for the most part apply to all forms of mobile sea, air, and landside platforms that are typically used to support environmental field activities.

Although the scope of this document is designed primarily around saltwater activities in and around Puget Sound, these guidelines could also be used successfully when conducting environmental field activities on open bodies of fresh water.

As a final note, it must be pointed out that no single positioning methodology is capable of meeting the positioning needs of all sampling programs under all possible circumstances. This is because (1) the instruments described herein can be used any number of different ways depending on specific project criteria, sampling location particulars, and predominant environmental factors, and (2) no methodology is without its inherent strengths and weaknesses.

The Global Positioning System (GPS) described in Chapter 4 is probably the most ideal overall methodology in use today, as attested to by the fact that it is used the most extensively by the various public agencies on their scientific excursions in Puget Sound. However, in the end, a successful station positioning effort depends totally upon the personal expertise of the individual navigator and the depth of his practical knowledge of a broad spectrum of positioning technologies.

Under agreement with the Puget Sound Water Quality Action Team (PSWQAT), these guidelines were developed with assistance from representatives of organizations that presently fund or conduct environmental studies in the Puget Sound region (see the preceding table, ‘CONTRIBUTORS TO THE GUIDELINES’).

2. PROJECT PLANNING

Proper station positioning is a critical component of sampling and data collection. Each sample matrix that is collected and analyzed is intended to be representative of a specific environmental locale and existing condition. Successful station positioning must therefore allow samples or data to be collected from new or historic sampling points within the expected accuracy limits as dictated by specific project requirements.

There are many basic factors that need to be addressed during the planning process including such elements as study objectives, expected accuracy, environmental considerations, and equipment costs and availability, to name a few.

All of these factors need to be considered prior to the sampling event to ensure that positioning methods do not compromise quality or interpretation of the data results. The initial estimate of positioning requirements should be re-evaluated later on in the planning phase to determine whether positioning limitations will require changes in the sampling program.

2.1 Program Objectives

The purpose of the study should be the first major factor that needs to be considered when evaluating possible positioning methods for an upcoming environmental sampling program. The program objectives will ultimately dictate the level of positioning accuracy that will be required for successful completion of the sampling effort.

It is important that all participants have a thorough understanding of program objectives. Field personnel should then be better equipped to evaluate their level of effort throughout the course of the sampling event with regard to meeting these objectives.

2.1.1 Program-Imposed Constraints

Various program-specific constraints may affect the decision when selecting suitable positioning methods. For instance, sampling time limitations may preclude more logistically demanding positioning methods, or lack of field crew experience with the proposed positioning system may compromise performance. Contractual obligations and budgetary limits could reduce flexibility, limit options for changes to the study design, or restrict station positioning choices. Care should be taken to recognize all program-imposed constraints and identify those processes that may be impacted during the course of the study.

2.1.2 Regulatory Guidelines

Some project criteria are derived from regulatory agency guidelines. One example is the EPA's Locational Data Policy (LDP) which they developed in 1991[1]. This "is an official EPA directive which applies to all facilities, sites, and monitoring and obervation points regulated or tracked by EPA under Federal environmental laws." (Hess, 1998) As a result, King County's wastewater treatment facilities support various environmental monitoring efforts as required under their

[1] More details pertaining to this directive may be found in the first section under '7. REPORTING REQUIREMENTS'.

NPDES permit conditions. In doing so, King County incorporates the appropriate regulatory guidelines into its own project criteria wherever applicable.

When planning projects where regulatory guidelines must be followed, it is important to be aware of and abide by any appropriate positional accuracy standards that have been formally identified by the local regulatory agency.

2.2 Positional Accuracy Concerns

Achievable accuracy can be compromised in a variety of ways. For instance, map accuracy and the ability to locate a reference point on a map or chart are two of the largest potential sources of positioning error. Regardless of the positioning method used, positional accuracy can never exceed the accuracy of the reference point locations that were used to plot or calculate the fix.

High-resolution, scaleable aerial photographs, if recent, can be one way of verifying map accuracy. These photographs can either be converted to digital imagery and displayed in real time with GPS or LORAN location information, or they can be digitized and set to a grid-type coordinate system for producing electronic shape files for use by a Geographic Information System (GIS) or other geographically-oriented computer system (Daniels, 1998). The line map files that the King County Environmental Laboratory presently use in conjunction with its navigational software originated from just such a set of digitized aerial photographs produced by the City of Seattle. The Washington State Department of Natural Resources may also have sets of digital orthophotos that could be made available for use by other research groups.

Historically, National Ocean Service nautical charts are commonly used when navigating on the inland waters of Puget Sound. However, with the advent of other types of grid-type coordinate systems such as State Plane, it should be understood that standard navigational charts have their limitations. For instance, if a coordinate system other than latitude/longitude is preferred, coordinate conversion will always be an issue. This is because the lat/long coordinate system is non-linear in nature; surface distance varies in length depending on the degree of latitude or longitude due to the ellipsoidal shape of the planet.

Also, while these charts accurately show the location of important navigational reference points, caution is needed when plotting new reference points near the water as shoreline features are often inaccurately represented. This is because the shape of the shoreline area is constantly being altered due to erosion and accretion, which is often related to longshore transport activities or manmade structural alterations.[2]

Achievable accuracy can also be compromised by such adverse physical factors as strong currents, heavy boat traffic, and physical line-of-sight obstructions as these conditions can affect a vessel's ability to maneuver and hold on station. Acceptable limits for a particular study may be exceeded if the effects of site location on positioning accuracy are not considered during design of the sampling program.

[2] Shoreline areas, as represented on navigational charts, may be 20 years or more out of date beyond the publication date. (Daniels, 1998)

When sampling stations occur in a grid, along a gradient, or in highly heterogeneous areas, it is important that station separation be maintained. Minimum separation should be defined by the diameter of the probable sampling area, at a 95 percent probability level, at each station. Spatial resolution of station locations is limited by positioning method accuracy, depth, and wire angle.

2.2.1 Absolute and Repeatable Accuracy

The type of positioning accuracy that is needed to meet specific sampling objectives should be identified during the initial planning phase. For instance, the difference between absolute and repeatable accuracy can be significant, as the first determines that level of accuracy by which a geodetic point can be acquired, while the second defines the level of accuracy pertaining to station reoccupation. Some of the study design or location factors may affect one type of accuracy but not the other. It is important to identify which type of positional accuracy is of concern at the outset of the study design phase. Positional accuracy is addressed in greater detail in the following sections pertaining to specific positioning methodologies.

2.3 Environmental Considerations

Since the nature of the study area will be a determining factor when selecting the most feasible positioning method, this element should be addressed at the outset of the planning phase. It is important to note that the ability of a specific positioning method to achieve its highest projected accuracy depends, in part, on site-specific conditions.

2.3.1 Reference Point Criteria

All positioning methodologies depend on the ability to refer back to external points of known position. Even self-contained inertial navigation systems must be periodically re-calibrated with another type of positioning system that utilizes external reference points. Therefore, the availability of known, fixed reference points for establishing acceptable lines-of-position (LOPs) within the study area need to be determined for each station. These candidate locations should ideally be able to provide coverage of the entire sampling area. Estimates of position errors should be based on anticipated LOP or angle errors expected at each sampling station. Limiting factors within the survey area and at individual sites should be identified, based on an inspection of each reference site. Line-of-sight obstructions, boat traffic, competition from other transmitters, air-water boundary irregularities, accessibility, and security should also be evaluated.

The spatial relationship between each proposed sampling station to its respective reference sites is critical as it effects positional accuracy. In essence, the level of accuracy of a positional fix using any two reference points increases as the angle between the LOPs approaches 90^o. Consequently, the level of accuracy will vary from one sampling station to the next as the juxtaposition of the moving vessel relative to the two reference points changes. Ideally, the navigator should have access to three permanently-fixed reference points (two are necessary; the third provides confirmation) strategically spaced around the study area and within the operational range of his positioning equipment for each sampling station.

Depending on the area of study, a preferred positioning method may not be usable or sufficiently accurate at all locations. As examples, LORAN-C is not reliable in some parts of Puget Sound as reception can be poor at times and accuracy can vary significantly from one area to the next. Since the accuracy of optical systems decreases at greater distances from shore, these methods may not be satisfactory for use in open water away from land. For these reasons, the geographic location and adjacent terrestrial characteristics of the study area are a principal determinant when evaluating different positioning methods.

Finally, the level of accuracy is dependent upon the category of environmental activity that is to take place. These activities can be categorized as follows:

- single point
- lineal
- areal
- point source

2.3.2 Single Point Activities

Many types of environmental activities on Puget Sound take place at specific geographic points identified by a single set of coordinates. Some of the more common marine science activities are discussed below.

2.3.2.1 Water Column Sampling

The collection of samples and the taking of *in situ* measurements within the water column are common elements of many environmental studies in Puget Sound. Unlike the underlying sediments, the water column is a dynamic medium that is constantly in motion. Defining the physical and/or chemical characteristics within these moving water parcels is a common sampling objective for many projects.

For this kind of sampling operation, absolute accuracy is usually not as critical as how the stations are distributed spatially, especially in the main basin areas away from direct source inputs. This is because at any given geographic point, physical and chemical characteristics within the water column are continuously changing hour-by-hour. The technique of simply drifting with the tide while on station is one way of helping to insure that the collected samples and measurable data are representative of the same water parcel throughout the sampling sequence.

Absolute accuracy is usually more critical in nearshore waters when the study objective is to determine potential environmental impacts from a specific source input such as an outfall or a river. This is because the geographic positions and spatial distribution of the sampling stations are directly related to the spatial distribution of contaminants from that source point.

In summary, the geographic location of the study area and its relationship to neighboring land masses and local source inputs should be taken into account when establishing accuracy limits for water column sampling projects.

2.3.2.2 Subtidal Sediment and Benthos Sampling

Absolute and repeatable accuracies are typically of greater concern when sediment or benthos sampling because,

- accurate geographic positioning is necessary when evaluating possible environmental impacts from source point inputs at a specific site, and

- except in areas of high scouring activity, marine sediments are relatively stationary, which means that a high degree of positional accuracy is required to precisely sample discrete sampling points that are within close proximity to each other, or to repetitively sample at the same sampling point.

It is important to note that for bottom-sampling operations, positional accuracy, station boundary sizes, and sediment variability are inextricably linked together. For instance, the broad central bottom areas of Puget Sound are composed primarily of homogenous depositional sediments. At these greater distances from terrestrial inputs, concentration gradients are more gradual so a reasonable strategy may be to extend station boundaries. This means that fewer stations would be necessary to represent a specific study area and a less accurate positioning system could probably be used for station acquisition.

Conversely, stations in nearshore waters must have tighter perimeters; the bottom sediments here are more heterogeneous as they are directly impacted by terrestrial source inputs. Once again, the geography of the study area is an important consideration.

The chemical and statistical analyses to which the collected samples are subjected should also be considered when determining the required navigational accuracy. For instance, if a gradient of environmental effects is suspected but the analytical technique cannot measure small differences in the value of a specified variable, sampling stations may need to be located farther apart. On the other hand, variability within a station's boundaries may be more difficult to discern if the positioning method lacks sufficient accuracy. This means that for variables having a 'patchy' distribution, the patch size could be smaller than the area defined by the repeatable accuracy of the positioning method, resulting in replicates sampled across community or physical boundaries. These conditions may not be noticed in the field and could result in misinterpretation of the data results.

Statistically, there is no theoretical or practical way of proving beyond doubt the level of heterogeneity for a specific area of marine sediments as the degree of spatial variation for a given variable cannot readily be established (Georgianna, 1997). As a consequence, more replicate samples may be needed to better characterize a sample area, especially if less accurate positioning methods are used. In any case, statistical comparisons using replicate samples from heterogeneous stations deserve special attention. The effects of positional accuracy and how it relates to probable sampling area should be considered in the study design.

2.3.2.3 Instrumentation Emplacement and Retrieval

Some autonomous instrumentation, such as current meters and sediment traps, are designed to be deployed on the bottom to operate independently for extended periods. With these operations, it is essential that careful thought be put into how these devices are to be relocated for retrieval purposes. In a protected, shallow-water area, the simple expedient of marking the underwater location with a surface buoy might be acceptable. In deeper water away from shore or where there is heavy boat traffic, a navigational system having a high degree of repeatable accuracy will be required.

Plans should also include a secondary means of instrument relocation and retrieval. For example, an underwater pinger (locating transmitter) or a backup release system could be mounted on the instrument. A snag line or ground cable could also be laid out across the bottom on a known bearing between the instrument and a small secondary anchor in case grappling is necessary.

2.3.3 Lineal Activities

Some projects require that certain activities (e.g., plankton tows, trawling and dredging operations, etc.) take place along one or more transect lines. This means that a navigational system must be able to measure both the start and finish of each transect leg. The selected reference stations must also be accessible from both ends of each projected transect line. If the position of the towed device relative to the vessel is important, it can be calculated if the wire angle, length of wire out, and depth of the device are known constants. In shallow water, a tag line and surface float can also be attached directly to the underwater device to provide a visual reference and to recover the device should the tow line part.

Other kinds of activities might entail that the vessel's position be tracked continuously over the course of a transect line (which may not be straight if the vessel is following a bottom contour line). During bathymetric operations for instance, the navigational system must be able to rapidly supply updated fixes for recording onto a data logger which will also be simultaneously recording synchronized fathometric data.

The same kinds of requirements also hold true if the vessel is operating a Remote Operated Vehicle (ROV). Since an ROV is self-propelled, it is standard practice to include a separate underwater navigational system to continuously monitor the ROV's position relative to that of the support vessel. Once again, the recording of positional data will need to be synchronized with the video records and other sensor data.

2.3.4 Areal Activities

Activities that take place over a specified area will for the most part have the same positioning requirements as the single point and lineal activities described above. It is common practice when areal sampling to use sampling strategies that incorporate groups of sampling points or parallel rows of transect lines.

In some instances, not all areal sampling strategies will be centered around a symmetrical distribution of sampling points. For example, a study design for a saltwater marsh might require that sampling sites have a distribution pattern that is species- or habitat-specific.

When intertidal sampling for certain species of shellfish, sampling sites will often be at irregular intervals and may change year-by-year as some shellfish beds die out while others start up in new locations. If the location of beach sediment sampling activities is based upon grain size criteria, these sites can be expected to shift with the seasonally-changing beach substrate. Study objectives and the nature of the environment where the study will take place are important considerations.

2.3.5 Site-specific Activities

Some marine sampling programs are designed to evaluate the level of potential environmental impact at specific sites in and around Puget Sound. These kinds of studies include such activities as contaminated site investigations, restoration site studies, and the evaluation of effects from localized point sources such as storm drains and Combined Sewer Overflows (CSOs). Ideally, the ideal positioning system should have a high absolute accuracy as the locations of the source points and adjacent sampling sites often need to be plotted on pre-existing city and topographical maps. Also, the spatial distribution of sediment pollutant concentrations will ultimately need to be accurately defined.

The sampling strategies for these types of studies can be developed in a number of different ways. For instance, station distribution could be in the form of a uniform radial or grid-type pattern. The sampling strategy could also be centered around bottom contour or water current characteristics. If time was not a limiting factor, an initial round of samplings could be collected and analyzed on a small scale as a way of determining where the main body of samplings should take place, based upon the initial findings.

2.4 Equipment Availability

Equipment availability is an important consideration with regard to study design. For instance, a vessel's cruising speed, its ability to maneuver, and the type of positioning and sampler-deployment equipment that it carries could be a determining factor in how successfully and timely a particular sampling program would be carried out. If a positioning system already exists on the vessel, it should be evaluated to determine whether its accuracy is adequate for the sampling program.

If purchase of a system is warranted, additional factors should include compatibility with existing equipment, ability to accommodate future system expansion, and availability of ancillary items (e.g., data logger, plotter, tracking monitor, or computer). Potential use of the system for other types of projects may also be relevant.

If budget constraints are an issue or if the upcoming study is a one-time-only event, the renting or leasing option may be preferable. If so, equipment calibration, service, and training should be provided locally, and reservations should be made in advance.

2.5 Training Considerations

Once a suitable positioning method has been selected, the proper setup, calibration, and operation procedures should be reviewed by all equipment operators. If the appropriate equipment is already located on board the vessel, at least one member of the field crew in addition to the ship's navigator should be familiar with the positioning method.

If the scientific team is supplying the positioning equipment, appropriate training should be provided, if needed, to ensure proper equipment operation and accurate recording of the positioning data. A backup method should also be available on short notice to avoid loss of ship time if the primary method fails.

2.6 Positioning Methods Summary

In the Introduction section, the point was made that no single positioning system will universally meet the needs of all who perform work on Puget Sound; each positioning method has its own unique set of characteristics, making it more suitable for some marine activities and not others.

To better aid the user when selecting the most appropriate positioning method, the following table attempts to summarize some of the more outstanding comparisons that can be made between the various methods categories that are discussed in this document.

SUMMARY OF STATION POSITIONING METHODS

Methods Category	Text Sect.	Areas Used	Accuracy/ Precision[3]	Approx. Costs[4]	Advantages	Disadvantages
Line-of-Sight	3.1.1 3.1.2	nearshore	5 ft - > 50 ft	$0	Requires no additional equipment or staff.	Must create new stations on-site. Visual references must be located on chart before plotting. Good visibility and target quality necessary.
Optical-Mechanical Range Finders	3.2.1	nearshore	1% - 10% of range	$200	Minimal equipment costs. One person can operate with minimal training. User can calibrate instrument.	Accuracy limitations, especially at greater distances.
Laser Range Finders	3.2.1	short distances	< 1 ft	$2000	High accuracy and resolution. Targets do not require prism array.	Can produce erroneous readings from secondary returns.
Azimuth-Azimuth: Dual Theodolite	3.2.2	nearshore	± 5” - ± 20”	$5000 - $8000	Instrument accuracy is survey quality. Good portability. Service and rental are local.	Measures angles only. Susceptible to pathway interferences, low-light conditions. Difficult if target movement is rapid or erratic. Two onshore reference stations must be occupied at same time.
Range-Azimuth: Total Stations & EDMIs	3.2.3	nearshore	± 2” - ± 5” ± 3 - ±5mm	$10,000 - $15,000	Measures both angles and distances. Instrument accuracy is survey quality. Good portability. Requires only one occupied onshore ref. station. Service and rental are local.	Susceptible to pathway interferences, low-light conditions. Difficult if target movement is rapid or erratic. Auto-trackers could have difficulty holding on target at times.
Independent Microwave: Radar	3.3	open	±1° - ±2° 50 ft - 150 ft	$8000 - $15,000	Commonly found on all sizable vessels. Can use in all weather conditions and at night.	Accuracy limitations: cannot use for precision positioning. Requires two or more fixed, high-definition targets.
Dependent Microwave: Transponder Systems	3.4.1	open	±3 ft - ±10 ft	> $40,000	Good accuracy if onshore transponders well placed. No visibility or range constraints. Positioning data in real-time, automatically updated.	Susceptible to pathway interferences. Requires transponder setup and power maintained. Very expensive to buy but can be rented locally.
LORAN-C	3.4.2	open	±50 ft - 300 ft or more	$3000 - $5000	Low cost, all-weather, easy to use. Destinations can be loaded beforehand. Shows speed and bearing info.	May not be in existence much longer. Often poor absolute accuracies. Inconsistent repeatable accuracies.
GPS[5] (below survey quality)	4.	open	±2 ft - ±30 ft	$5000 - $10,000	Moderate cost, good accuracy, very adaptable. Data can be corrected in real-time or post-processed. Technology is expanding rapidly; great potential.	May see interferences near large steel structures and AM towers or under cover (e.g., under piers, trees, etc.)

[3] When using shore-based electro-optical systems (e.g., theodolites, total stations, etc.), the ability of the vessel to maneuver will be the limiting factor rather than instrument precision. Except for LORAN-C and GPS, positioning method accuracy will be determined from the level of accuracy by which the occupied reference points were surveyed in.

[4] Equipment costs may vary significantly depending on make and model, accessory options, and whether it is new or used.

[5] Survey results of the latest GPS receivers on the market are reported each January in the publication, GPS World, Advanstar Communications Inc., 859 Willamette St., Eugene, OR 97401-6806. They can also be found on the Internet: http://www.gpsworld.com/about/contact0.htm

3. TRADITIONAL STATION POSITIONING METHODOLOGIES

A number of different navigational techniques have been used successfully on a variety of diverse marine activities to establish geographic positions in Puget Sound waters. These methodologies may be categorized based on the use of one of the following applications:

- visual lines-of-sight and other identifying features
- optical and electro-optical range and/or azimuth devices
- independent and shore-based dependent microwave systems
- long-range, radio navigation system (LORAN-C)
- underwater (acoustical) systems

Many traditional navigational methodologies require that vessel positions be plotted on nautical charts to establish geodetic placement. These plots graphically display known angles and ranges through the use of lines-of-position (LOPs) and circles-of-position (COPs). These plotting techniques will be discussed further in the following sub-sections.

3.1 Line-of-Sight and Other Visual References

A variety of visual reference methodologies may be used in nearshore waters, especially where a suitable selection of unique shoreline characteristics and/or manmade structural features are present (e.g., in and around urban and industrialized embayments and rivers).

3.1.1 Line-of-sight Intersects

One common method for establishing a positional fix in nearshore waters is to create an LOP based on a line-of-sight. In essence, a line-of-sight is created when two fixed visual targets are brought into alignment on a common axis with the vessel's own position.

When two or more lines-of-sight have been established from the stationary vessel, the point of intersect will then become the vessel's new position (refer to Figure 1.). An effective and economical way of documenting a specific line-of-sight (for station re-occupation purposes) is to simply take a shipboard photograph while the target pair is in alignment. A position may also be plotted if the respective background and foreground targets are accurately depicted on a scaled chart.

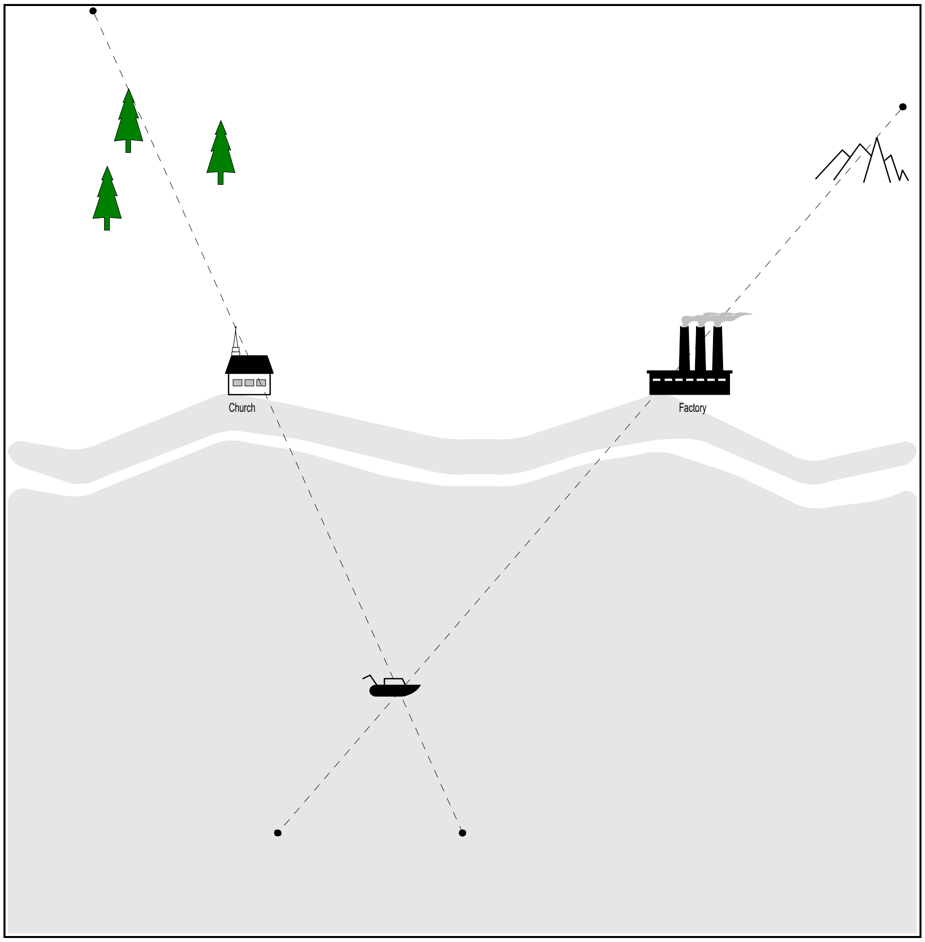

Figure 1. Multiple Line-of-Sight Intersect

3.1.2 Line-of-sight/Compass Bearing Intersects

It is not uncommon to find just enough visual onshore targets to create only a single line-of-sight. In this case, an LOP is first established from the line-of-sight. A close-to-perpendicular compass bearing is then shot off of a separate fixed target while the vessel is occupying the LOP (refer to Figure 2.). If it is convenient to do so, swinging the ship's prow onto the target is an effective way of bringing the binnacle into alignment to obtain a direct bearing readout.

This method also adds flexibility in that viable compass bearings may be taken at multiple positions along the vessel's LOP. The method should only be used if compass accuracy is a known factor, including the allowance made for the magnetic deviation currently in use at that time. All bearing information must be properly recorded.

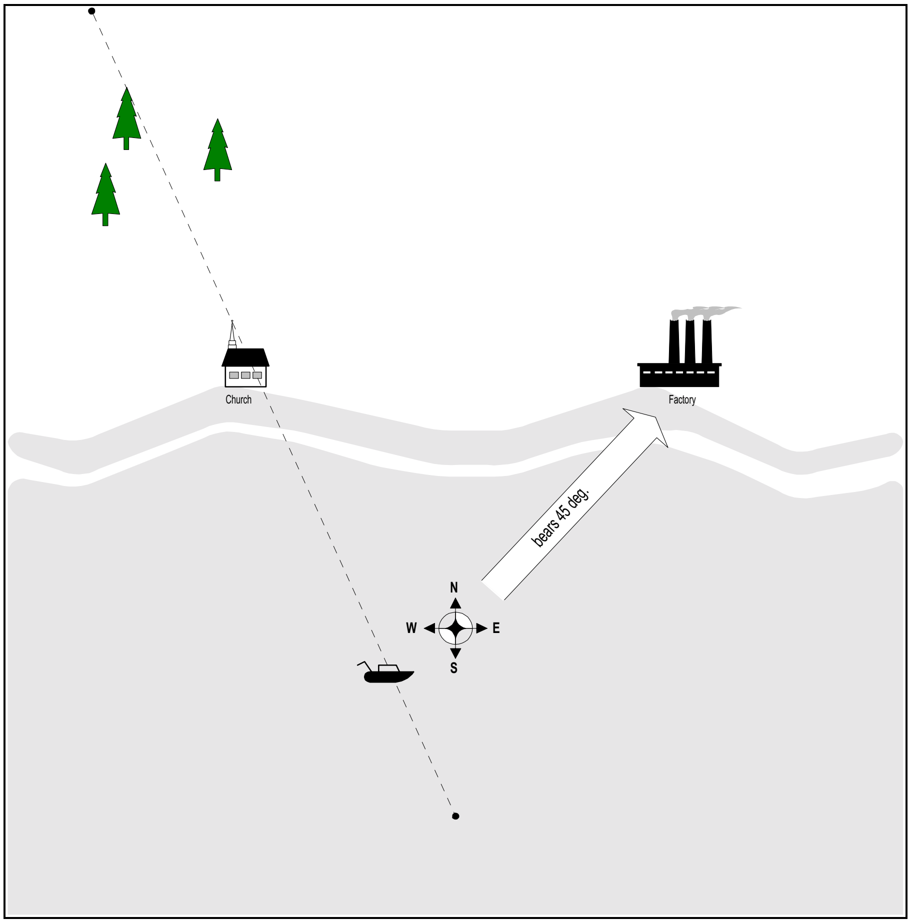

Figure 2. Line-of-Sight/Compass Bearing Intersect

3.1.3 Other Visual References

Visual referencing techniques are particularly useful during intertidal sampling events. Almost any prominent landmark can be of potential value for locating a beach station, especially when used in association with distance and/or bearing measurements. When selecting a suitable landmark, permanence and uniqueness must always be considered.

3.1.4 Strengths and Weaknesses

The strengths and weaknesses of line-of-sight positioning methodology include:

- New station positions can only be created beforehand if the respective visual targets can be pre-selected from a chart, or if another positioning method that does not rely on visual references is used.
- Positions cannot be plotted if the visual references cannot be accurately located on a scaleable chart.
- Good visibility and quality of target (i.e., good target definition) are necessary.

- Requires no additional equipment or staff.

3.1.5 Accuracy and Precision

The degree of relative or repeatable accuracy when positioning by line-of-sight relates directly to the distance ratios between the vessel, the foreground target, and the background target: Accuracy is increased when the ship-to-foreground-target distance is reduced and/or when the foreground-target-to-background-target distance is increased[6]. For this reason, the expected range of precision for line-of-sight positioning could be anywhere between approximately $\pm$ 5 feet to well over $\pm$ 50 feet.

Absolute accuracy cannot be established without the use of another positioning method that is capable of establishing the vessel's position relative to one or more geographic reference points.

3.2 Optical and Electro-Optical Range-Azimuth Systems

A number of different optical instruments are readily available that can be used for vessel positioning purposes. They range from fairly simple mechanical devices to the more elaborate electronic instruments that precisely measure not only the range (distance) to a target but also the vertical and horizontal angle (i.e., bearing or azimuth). These systems may include automatic data recording, conversions, and computations.

As with all optical distance- and angle-measuring instruments, the accuracy decreases as the operational distance increases between the survey point and the target vessel. For this reason, these instruments probably give the best positioning results for operations taking place in nearshore waters within a 3-mile range.

3.2.1 Range-Range: Range Finders

The traditional range finder is a simple and relatively inexpensive (less than $200) optical-mechanical device which is designed to measure ranges to distant objects. In essence, the slant distance is read off of the instrument scale once the split-image has been focused on a specific target. To minimize measurement subjectivity, a second operator should verify the initial readings of the first at the start of each surveying day.

A vessel can plot a positional fix by trilaterating from two known ranges to separate fixed shore targets. This is accomplished by swinging an arc, or circle-of-position (COP), off of each of two or more shore targets with the radius of each arc being equal to a measured range. The point of arc intersection would then establish station position. A fix can also be plotted from a single range if the vessel can accurately measure both distance and bearing to a single fixed shore target.

A recent addition to this equipment category is the hand-held, short-range (less than 1000 feet), laser range finder. These electronic instruments are more expensive ($2000) than the simpler

[6] It is important to note that for all visual positioning methods, accuracy decreases as distance increases between the vessel and the onshore reference points.

optical devices mentioned above but they are easy to operate and their greater accuracy will measure to within a tenth of a foot.

3.2.1.1 Strengths and Weaknesses

The strengths and weaknesses when using optical-mechanical range finders include:

- Equipment costs are minimal.
- One person can operate the instrument with minimum training.
- Accuracy limitations, especially at the longer ranges, may prohibit its use on many projects.
- Instrument can be calibrated by the user.

The strengths and weaknesses when using laser range finders include:

- Equipment costs are significantly higher but accuracy and resolution are much better than that of the mechanical range finder.
- Targets do not require a prism array; the exposed surface of almost any target will provide a sufficient return.
- For those targets in close proximity to objects having good reflective surfaces, more than one reading may need to be taken at different orientations to the target to minimize errors induced from secondary returns.

3.2.1.2 Accuracy and Calibration

Two factors that govern instrument accuracy when using the optical-mechanical range finders are operational distance and instrument quality. As an example, an instrument with a 1000-yard maximum range could be expected to deliver accuracies of ±1 yard at 100 yards (1% error) and ±100 yards at 1000 yards (10% error) (Lietz, 1991). This type of instrument is, therefore, better suited for work in nearshore waters within close proximity to fixed, onshore targets.

The mechanical range finder should be checked and adjusted for accuracy prior to start of a survey. Usually, this is easy to do by focusing in on a target of known distance, then adjusting the calibration screw, if necessary. The laser range finder may require servicing if its readings are questionable or if it cannot be calibrated by the user.

3.2.2 Azimuth-Azimuth: Theodolites and Transits

Theodolites and transits are tripod-mounted, optical devices that precisely measure horizontal and vertical angles. Technically, theodolites are used primarily by surveyors for triangulation and traverse work, while the building industry uses transits for double centering, extending lines, and checking angles during the construction phase (Lietz, 1991). Since station positioning activities more closely parallel surveying techniques, the theodolite may be better suited for this kind of work.

Since a theodolite by itself has no ranging capabilities, at least two angles must be shot either simultaneously or while the vessel is stationary at separate survey points along a baseline on shore to establish a vessel's position (see Figure 3.). Each theodolite uses the baseline for its zero-angle adjustment. Unless the vessel is able to maintain a stationary position for an extended period to allow the onshore party to move to the next survey point, this method will require that two survey points be staffed and equipped at the same time. Visual or radio communications between the shore parties and the vessel are an additional requirement.

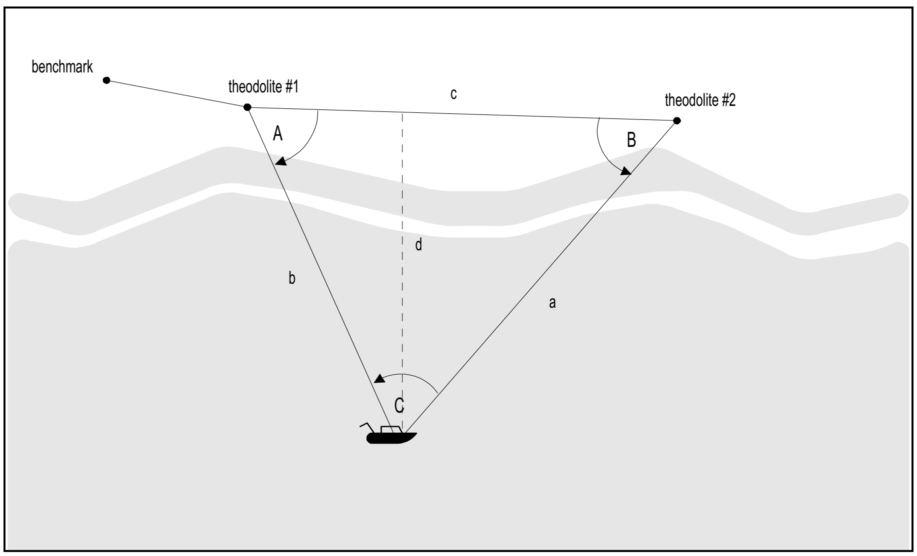

Figure 3. Azimuth-azimuth: the Dual-Theodolite Method

The vessel's position can triangulated by plotting the onshore survey points, the respective baseline between them, and the measured angles to the vessel on a navigational chart. The position, or fix, will then be established at the point of LOP intersect.

An alternative to plotting would be to mathematically calculate the coordinate fix. For this purpose, the standard trigonometric *sine/cosine/tangent* relationships may be used to calculate the angle-of-intersect, the distances of each leg, and/or the distance of the vessel from shore (i.e., from the baseline).

With reference to Figure 3., the angle-of-intersect is found by,

$$\angle C = 180^{o} - \angle A - \angle B$$

the distance of the LOP from Theodolite #1 to the vessel is then,

$$\frac{b}{\sin B} = \frac{c}{\sin C} \qquad \text{(solve for side `b')}$$

and finally, the distance from the vessel to the baseline (perpendicular) is,

$$d = b * \sin A$$

3.2.2.1 Strengths and Weaknesses

The strengths and weaknesses of the dual theodolite method include:

- The theodolite measures only horizontal and vertical angles and, though it is very accurate, this method requires that more than one onshore site be used to establish vessel position.

- Pathway interferences (e.g., fog, rain, heat waves, etc.) or low-light conditions can prohibit target sighting from a prescribed survey point.

- Rapid or erratic target movement may make it difficult to obtain accurate angles.

3.2.2.2 Accuracy and Calibration

When positioning with theodolites, the positioning error should be within $\pm$ 3 feet if the accuracy of the horizontal angle is $\pm$ 15 seconds, the intercept angles are near 45^{o} (resulting in intersecting LOP angles of close to 90^{o}), and the operational range is within 3 miles.

Instrument calibration can be verified by re-shooting known target angles. Questionable measurements may require professional servicing of the instrument.

3.2.3 Range-Azimuth: Total Stations and Theodolite/EDMI Combinations

A Total Station is an all-in-one survey instrument which can accurately measure not only horizontal and vertical angles (i.e., bearings and elevations), but distances as well. This added feature allows a surveyor to determine the position of a target from a single site on shore (refer to Figure 4.). A theodolite can also be used to measure both angles and ranges with the inclusion of a modular Electronic Distance-Measuring Instrument (EDMI). The theodolite upgrade is a good option if the theodolite is already owned; purchase of an add-on EDMI would be far less than buying a $10 - 15,000 Total Station.

The distance-measuring component of the above instruments typically uses an infrared rather than a laser beam. Infrared systems are very compact and energy-efficient and can measure distances up to several miles, but the target requires a prism array. Prisms are unnecessary when using the small, hand-held laser devices, but these short-range units are only useful up to several hundred feet.

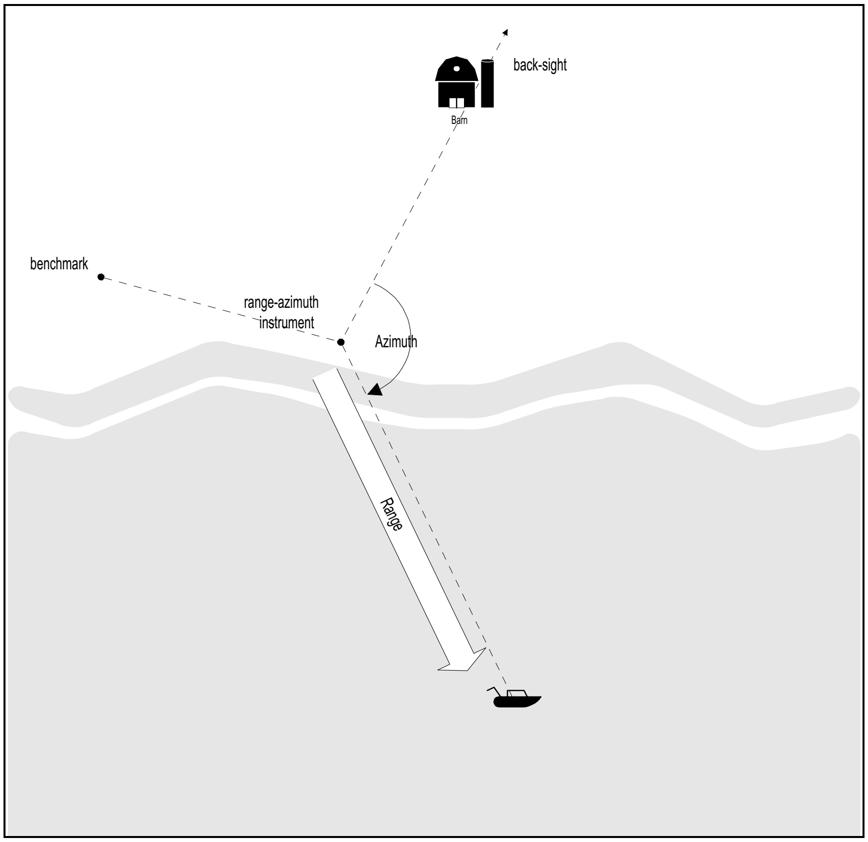

Figure 4. Range-azimuth: Positioning from a Single Survey Point

Total Stations (especially the newer models) are adaptable instruments that can be used in a variety of ways. For vessel positioning applications, one reliable method is for the surveyor to call in coordinate data or direct vessel movement via two-way radio communication with the vessel. When interfaced with a compatible transmitter module, positional information can be transmitted directly to the vessel. The more advanced models can interface with a laptop computer and modem combination to provide real-time functionality such as requesting and transmitting data, and selecting and activating measurement modes and functions (Sokkisha, 1990).

These instruments can also accept different data logging and electronic field book devices capable of performing trigonometric calculations such as automatic slope reduction of distances, and they can quickly convert between different coordinate formats (Sokkisha, 1990). After the raw range-azimuth (polar coordinate) data have been collected, it can also be converted later to the appropriate grid coordinate system (refer to the last part of Section 3.2.2 Azimuth-azimuth: Theodolites and Transits).

3.2.3.1 Auto-tracking

For those projects where staffing an onshore survey site is not suitable, there are range-azimuth systems available with auto-tracking capabilities. Once manually aligned to the target's prisms, the instrument will automatically track unaided. If for some reason the target is lost, the instrument will automatically go into a seek mode where it follows a programmed search pattern until contact is re-established.

Although labor costs may be reduced since an auto-tracking device is more automated, the higher degree of equipment complexity would mean higher equipment costs ($40 - 75,000) along with the increased potential for higher maintenance costs.

3.2.3.2 Reflecting Prism Arrays

Before a Total Station or EDMI can determine distance, the transmitted infrared beam[7] must be reflected back to the instrument from the target in sufficient strength that time-over-distance calculations can be performed. To accomplish this, the target must have one or more reflecting prisms mounted in such a way that they will be in direct line-of-sight with the survey crew on shore. More prisms mounted on the same plane will give a higher return of the transmitted infrared beam. Stepping up from one, to three, to nine prisms increases the return, and consequently the ability to measure at greater distances, from 75 to 80% with each step up in number of prism sets (Sokkisha, 1990).

If a maneuvering vessel is going to be changing orientation frequently with respect to the onshore survey party, multiple prisms can be mounted in a 360^{o} configuration. Such an omnidirectional array presents overlapping prism angles to the ranging instrument in such a way that there will be an infrared return, regardless of vessel orientation. However, as only a portion of the prisms is available at any one time, the operational ranges would not be as great for this particular prism configuration.

The King County Environmental Laboratory has successfully used a 360^{o} array in conjunction with a Lietz SET 5 Total Station on a number of projects in the Duwamish River and Elliott Bay. The prism array was typically bracket-mounted directly above the vessel's descent-line which avoided having to compensate for horizontal offsets between the sampling point and the prism array. Distance did not turn out to be a limiting factor.

3.2.3.3 Beam Angles and Measuring Times

Selection of the most appropriate range-measuring device should be governed by which model is designed to operate best within the minimum/maximum ranges that will be encountered during the course of a survey. For instance, infrared beam width is an important consideration. To conserve power, some of the more far-ranging models will often use a relatively narrow beam width. This means that for close-in measurements, a narrow beam may be difficult for the operator to train on the prism array for the time it takes to acquire the distance measurement, especially if the vessel is pitching and rolling due to adverse weather conditions.

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[7] Infrared has the advantage over the laser-emitting equipment in that it is significantly more energy-efficient, even at distances of several miles, although it does require that the target mount a prism array.

Micro-processing speed is also critical. The longer it takes for the instrument to calculate distances, the longer the operator must track the target without breaking contact. Therefore, the most ideal models should have (1) a beam width which allows for easy close-in tracking, yet will meet the project's distance requirements, and (2) is fast enough to quickly acquire the target and provide frequent range updates Ideally, target acquisition should take place within 1.5 seconds with range updates every few tenths-of-a-second while in tracking mode.

3.2.3.4 Strengths and Weaknesses

The strengths and weaknesses when using range-azimuth instruments for positioning purposes includes:

- As only one onshore survey site is required to provide circular coverage of the area of operations, labor and equipment costs are significantly reduced; one experienced operator is usually adequate.

- Instruments are quite portable and can be used in inclement weather with minimum protection. They can also be used on a variety of different projects in and around nearshore waters but may be limited in range for those applications at greater distances from shore.

- Equipment costs are relatively high ($10 - 15,000), but maintenance and leasing facilities are available locally.

- Rapid or erratic target movement may make it difficult for the surveyor to obtain accurate distances and angles; auto-tracking systems may have difficulty maintaining and re-acquiring contact with the target.

- The potential for theft and vandalism may limit the selection of safe and secure survey sites when using auto-tracking equipment.

- Pathway interferences (e.g., fog, rain, heat waves, boat traffic, etc.) and low-light conditions can interfere with line-of-sight targeting from established sites on shore.

3.2.3.5 Accuracy and Calibration

Realistic accuracies are approximately three to six feet when positioning a maneuvering vessel. The maneuvering limitations of the vessel and the difficulty incurred when attempting to track on a moving target are the limiting factors rather than the instrument itself.

Since the timing circuit for measuring the response time between transmission and return of the infrared light beam is based on a precision quartz crystal oscillator, range accuracy is usually quite stable. Instrument accuracy can be readily verified by periodically re-shooting known target angles and distances. Questionable measurements may require professional servicing of the instrument.

3.2.4 Sextants

Sextant resection is an historic positioning method that has fallen by the wayside with the advent of modern-day electronic positioning equipment. For this reason, sextant usage warrants only brief mention.

The sextant is an optical-mechanical instrument that is capable of measuring both vertical and horizontal angles, depending on which way it is held. It utilizes split-image optics to measure the angle of separation between two distant objects.

For station positioning purposes, a sextant is commonly used to establish two horizontal angles between three fixed onshore reference points. A three-arm protractor, adjusted and locked on to these angles, can then be used to perform a ‘best fit’ to establish station location on a navigational chart, assuming that the selected reference points are also accurately represented.

Instrument quality, if its been recently calibrated, and the level of operator experience are all factors that can effect positioning accuracy. Since a sextant is an optical, hand-held device, platform stability is an important consideration; adverse weather conditions affecting this stability may well reduce the effectiveness of this method on board ship.

3.2.5 Vertical Measurements: Using Levels to Establish Beach Elevations

When positioning a vessel in Puget Sound waters, the vertical angle, or elevation, is usually not a major issue. This is because the relatively small gain in elevation from the waterline to that point on shore where a reference site would typically be located is normally not enough to introduce a significant degree of error for most marine applications. In any case, many of the newer electronic surveying instruments are capable of automatically compensating for differences in elevation by adjusting for slope reduction over distance.

One application where elevations may be critical would be for those projects centered around the intertidal zone. The King County Environmental Laboratory’s intertidal sediment sampling program is one such example. The purpose of this effort is to evaluate the annual changes in contaminant concentrations within the intertidal sediments adjacent to King County’s treatment plants.

Prior to sediment collection at each station, field personnel first use an optical level and leveling rod to locate the mean 6.5-foot beach elevation. These measurements are repeated for each subsequent sampling event to compensate for the varying sampling times and tidal heights incurred at each station. Repeated sampling at a consistent beach elevation helps to insure comparability between data sets.

With reference to Figure 5., the 6.5-foot beach elevation is established as follows:

1. Upon arrival at the beach station, the predicted tide height at that time is subtracted from the ‘target’ beach elevation of 6.5 feet. (For a minus tide, this operation becomes an addition:

subtraction of a negative number). The height of the level's tripod is then added to establish the overall rod height to be measured from the 6.5 foot elevation on the beach[8].

Example: 6.5 - 2 (for a predicted tide ht. of +2 ft.) +5.0 (ht. of level) = 9.5 ft.
then, 9.5 ft. - 5.0 (ht. of level) = the 6.5-foot mark at a +2 foot tide ht.

2. A ribbon or something similar is used to mark the leveling rod at the calculated height to provide a visual target for the level, which is mounted on a 5-foot tripod. (A 5-foot pole with a level mounted at one end could be a cheaper option.)

3. While the first field person holds the leveling rod vertical at the water's edge, the second person walks the supported level further from the rod and perpendicular to the waterline to increase the elevation, or closer to decrease it. At the point where the level can be sighted on the ribbon, the base of the level's tripod will be at the 6.5-foot tide height.

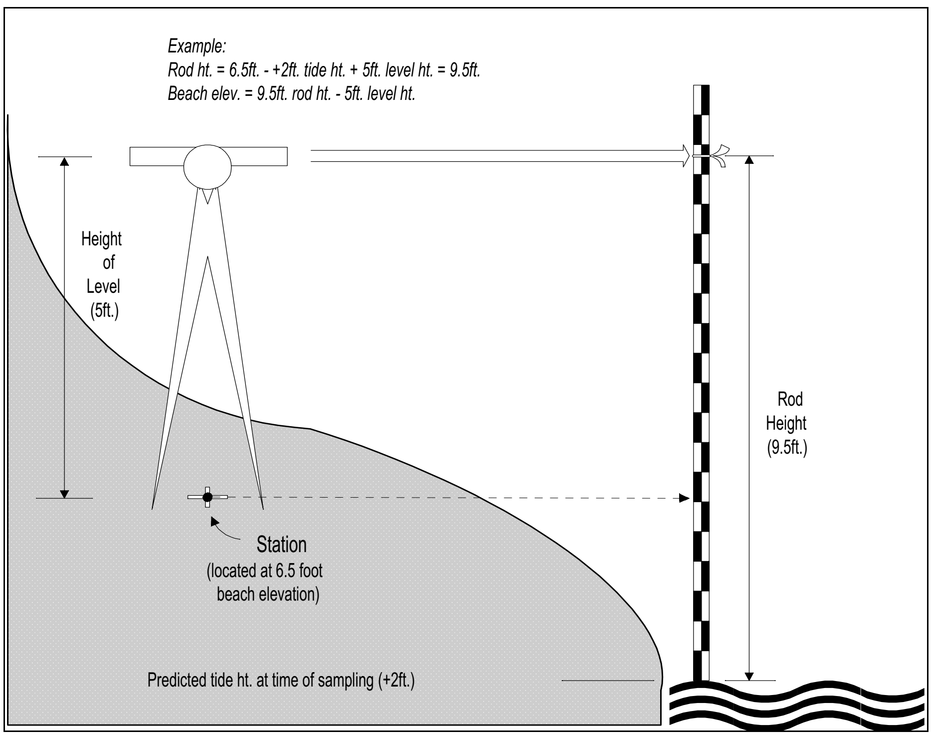

Figure 5. Beach Elevation Relative to Tide Height

If the elevation is not known, it can be calculated by setting the supported level on the point of interest, then shooting the rod at the waterline. The vertical rod height, after subtracting 5 feet then compensating for the present tide height, would be the beach elevation relative to a zero tide height.

[8] The height of the level is incorporated into the calculation for convenience only, as it would be quite awkward to peer through the level at ground level.

3.3 Independent Microwave System: Radar

The radar is a self-contained instrument capable of calculating line-of-sight distances to reflecting targets based on time difference measurements between the self-generated transmission and reception of microwave pulses. Relative angles can also be measured between two or more targets. Circular coverage is provided through the use of a single rotating antenna which continuously updates a visual display with each sweep.

Because radar gives a boat the ability to safely navigate during periods of low visibility (e.g., in darkness, rain, fog, etc.), this device has become standard equipment for all vessels operating in Puget Sound. From a positioning standpoint, this common navigational tool is often quite suitable for establishing and re-acquiring station locations. In addition, its operating range is many times greater than what is needed for most types of positioning activities within the enclosed waters of Puget Sound.

As with other instruments that measure distances from set locations, radar accuracy decreases as the operational distance increases. This equates to approximately 50 - 150 feet, with a bearing accuracy of about $\pm 1^{o}$, depending on quality of reflecting targets.

3.3.1 Range and Angle Errors

When using radar for positioning, one of the greatest sources of range error is attributed to the difference in quality of target resolution (definition) within a specific operating area. A radar's microwave transmission will reflect off of the first surface that it encounters at the water interface. Consequently, a permanently-fixed, sharply-defined reference point which is accurately represented on a nautical chart should make the best type of radar target. An example of a good landside reference is the vertical cliff face of a pronounced headland having good definition at the water's edge.

Unfortunately, most shorelines in Puget Sound present themselves more as a sloping, rather than vertical, target at the waterline. This means that radar ranges will vary with changing tide heights between a shoreline's leading edge and a fixed offshore sampling point. For this reason, tidal flats and delta areas do not make good radar targets. Another complication is that navigational charts may not give accurate representations of specific shoreline characteristics since shorelines are continually undergoing alterations due to longshore transport activities.

Range and angle errors can also be introduced through the effects of target distortion and shadowing. For instance, changes in the angle of approach and/or distance from a specific landside radar target can alter its visual perspective on the display. A sharply-defined headland as viewed from directly offshore may appear less defined when viewed at an angle in nearshore waters. The shoreline appears to take on more of a distorted and elongated appearance as the angle of approach of the transmitted microwave pulses becomes more acute. This is due to the shadowing effect of the adjoining landmass beyond the reflecting leading edge at the waterline. Radar may not be a reliable positioning method when operating close in to shore where only landside targets are available.

Permanently-fixed manmade and natural structures that stand out from shore and are free of its distorting influences make excellent radar reference points (e.g., Duwamish Head Marker, Restoration Point, etc.). Anchored navigational buoys, although they provide an excellent radar return, may not be suitable as they are free-floating. (Buoy scope and direction will fluctuate with changes in current velocity, direction, and tide height.) This type of target may be acceptable for short-distance positioning in shallow water, especially during high tide and static water conditions, or if other reference targets are available for position verification.

3.3.2 Variable Range Markers

A variable range marker is a radar accessory which is used to conveniently and accurately determine ranges to targets. It is typically represented as an adjustable, rotating, visual cursor on the radar's screen display. Placing the cursor on the leading edge of the target provides an immediate range readout to the target.

Ideally, it is advantageous for a radar to have a second variable range marker. Prescribed ranges to two separate targets can then be preset at the same time. The vessel would then be maneuvered in such a way that a 'best fit' was established to bring the vessel on station. Determinations for direction and rate of drift are also made easier.

3.3.3 Strengths and Weaknesses

The strengths and weaknesses when using radar for positioning include:

- Accuracy limitations may not be adequate for some projects requiring precision positioning such as when investigating potential sources of contaminant input to nearshore waters.

- The number and quality of radar reference targets may be inadequate in some operating areas.

3.3.4 Accuracy and Calibration

Range accuracies can be as little as $\pm$ 50 feet at ranges up to 5 miles, with a bearing accuracy of approximately $\pm 1^{o}$ or 2^{o} when using good-quality reflecting targets.

Accuracy can be verified by periodically checking bearings and distances to two or more clearly-defined, fixed reference targets. If the equipment is functioning properly, range accuracy is usually not an issue as the timing circuit is quartz crystal-controlled. When station positioning, overall positional accuracy can be enhanced by shooting ranges and/or bearings to three targets rather than just two.

3.4 Shore-based Transponder-dependent Systems

3.4.1 Line-of-sight Microwave Systems

Transponder-dependent, microwave systems utilize an onboard transmitter and two or more transponders (repeaters), located at known reference points on shore. Depending on the model, position is determined by measuring either the time interval between transmitted and received signals or the phase differences between arriving signals. Some models are capable of working in both modes.

3.4.1.1 Strengths and Weaknesses

The strengths and weaknesses of transponder-dependent, microwave systems include:

- Unlike optical systems, there are no visibility constraints although, since the signal pathway is radio line-of-sight, it can be interrupted or blocked by shipping activities, landside structures, etc.

- Range capabilities are more than adequate for Puget Sound waters.

- Onshore transponder stations operate automatically and do not need to be attended but, unless they are tied in to a shore power source, their batteries will need to be changed periodically to meet ongoing power requirements.

- Although the onboard transmitter utilizes an omnidirectional antenna, the transponder units are directional (30^o - 180^o beam angle, depending on model) which means that they must be carefully oriented when installed to adequately cover the area of operation.

- Positioning information is displayed and continuously updated in real-time on board the vessel.

- Some models have a time-sharing feature which allows for multiple use by more than one transmitter/user group.

- The equipment is quite expensive ($40,000 or more) but rental options are available locally.

- Equipment security may be an issue at some onshore transponder sites.

3.4.1.2 Accuracy and Calibration

For most models, expected accuracy is approximately ± 3 - 10 feet. Accuracy will be impacted if the geometry of the onshore reference stations has been compromised (the angles between stations should approach 90^o).

As a check for accuracy, the operator should re-calibrate the instrument over a known distance prior to the start of each survey event, or as the operation manual dictates.

3.4.2 Long-range, Low Frequency System: LORAN-C

LORAN-C, the successor to LORAN-A, is a long-range, low-frequency, radio navigation system that is used world-wide by land, air, and marine navigators. It was originally developed in the 1950s for the Department of Defense (DOD). In 1974, it was made available for civilian use. The DOD eventually replaced this system with the satellite-based GPS, the result being that all U.S.-owned LORAN-C overseas assets were transferred over to the host nations. The Coast Guard is responsible for the system's maintenance and operation within the continental U.S. (ODIN, 1997).

Every two years, the DOD and the Department of Transportation (DOT) publish the 'Federal Navigation Plan' which provides updates regarding the future plans for LORAN-C. The 1994 publication states that this system will continue to operate until the year 2000, at which time its continued existence will be re-evaluated (Schuster, 1997). Because this navigational system may soon become obsolete, it is suggested that all important sampling stations that have been previously acquired with LORAN-C only should be re-established via a second independent positioning method.

System operation is based on the ability of a shipboard LORAN-C receiver to measure the time difference (TD) between arriving signals from a specific chain of land-based master and secondary (slave) transmitters. Transmitted pulses from the master and two secondary transmitters create hyperbolic lines-of-position (LOPs), the intersection of which represents the vessel's position (USGS, 1995). Coordinate information is typically displayed either as a TD pair (with a resolution of 0.1 μsec), or as a lat/long calculation.

It is suggested that LORAN-C-generated latitude/longitude coordinates not be used when there is a need to establish a charted position. This is because the hyperbolic nature of the LOPs formed by the arriving signals is not compatible with a geodetic grid-reference system. LOP distortion may be aggravated by the existence of propagation anomalies commonly found in close proximity to nearby headlands or from electronic interferences encountered in and around urban areas. This means that a LORAN-C-derived fix may not always be consistently reproduced with the same degree of precision. For this reason, and because this system may soon be decommissioned, LORAN-C should never be used to locate a new position but only to re-acquire a position that has been previously fixed by a different navigational system. LORAN-C is generally considered to be a more consistent navigational aid when used out at sea away from continental landmasses.

For general water column sampling where sample collection within the same water parcel is a higher priority than establishing a precise fix, the King County Environmental Laboratory uses a Northstar receiver that has been upgraded to receive both GPS and LORAN-C transmissions. The receiver automatically switches between the two navigational systems, the strength and quality of signal reception being the determining factor. This is made possible because both LORAN-C and GPS are related to a common time standard, Universal Time Coordinated, or UTC (ODIN, 1997).

3.4.2.1 Strengths and Weaknesses

The strengths and weaknesses of LORAN-C include:

- A number of waypoints (destinations) can be loaded into the shipboard receiver beforehand, allowing it to calculate current speed and bearing along with distance and time-to-go to the next waypoint.

- Although the absolute accuracy of this system is probably not suitable for most scientific activities in Puget Sound, repeatable and relative accuracies may be sufficient for some projects.

- Although it is a low-cost, all-weather, navigational system with continuous signal availability, it should not be used as the sole positioning method due to possible discontinuance of LORAN-C after the year 2000.

- Intermittent signal interferences and 0.1 μsec phase shifts may be encountered at times, significantly impacting positioning accuracy.

3.4.2.2 Accuracy and Calibration

Overall accuracy is hard to establish as it can vary significantly between sites within the Puget Sound region. (An average estimate is usually stated as ± 50 - 300 feet or more.) Both signal-to-noise conditions and the geometric juxtaposition of the vessel in relationship to the transmitter baseline can effect the system's accuracy.

Absolute and repeatable accuracy can be verified by periodically comparing a current TD fix with a previous fix at a known position.

3.5 Underwater (Acoustical) Navigation

Some marine projects in Puget Sound may require that both a vessel's position and that of a submerged instrument be tracked. For these applications, the location of the underwater device is typically referenced back to the vessel's own position. Due to the significant density differences between the air and water environs, there is no single form of pulsed transmission capable of carrying positioning information that will readily pass through both mediums.

As a consequence, the standard approach for obtaining underwater geodetic coordinate data is to use some type of underwater navigation system below the surface that is capable of interfacing with the vessel's own atmospheric navigation system above the surface.

3.5.1 Relative Distance-bearing Systems

For those survey/sampling operations where both the floating platform and its associated activity occupy the same location (e.g., bathymetry, vertically-deployed sampling and water column measurements, etc.), knowledge of the surface position is usually sufficient for geographical identification. However, some activities often result in spatial separation between the surface position and that of the submerged instrument.

As an example, Remote Operated Vehicle (ROV) operations often use underwater navigational systems to continuously track the relative magnetic bearings along with both vertical and horizontal distances (slope distances) between the support vessel and the ROV. These devices are self-propelled and often work beyond the immediate vicinity of the vessel. The Trackpoint II, by ORE, is a popular short-baseline model that is reliable and easy to use. The visual display is typically used in the polar ("bulls-eye") mode to show bearing and slope distance to the underwater target from the surface vessel centered on the screen. The acoustical link is made between a transducer head, mounted on the outside of the vessel's hull, and a transponder (pinger) on the underwater device.

Some diving activities may require the same type of tracking capability as that described above. As an option, low-cost systems are available that use compact, hand-held, homing devices that can directionally track acoustical transmissions between divers, the support vessel, and/or other underwater targets.

Another type of more sophisticated underwater positioning system operates in conjunction with an array of transponders (also called pingers or beacons) located at known points on the bottom. The surface vessel keeps track of the juxtaposition of the submerged target as it operates within the boundaries fixed by these area-wide transponders. These systems can be quite expensive.

An optimum system configuration should incorporate a user-friendly visual display, oriented to magnetic north, which graphically shows directional changes in the underwater positional fix in relationship to changes in the surface fix. Provisions could also be made for simultaneously recording both the underwater and the surface positional fixes under the same universal time format.

Some marine activities do not require an underwater navigational system to keep track of a submerged instrument. Side-scan sonars and sub-bottom profilers are two examples of instruments that use towed packages to collect geophysical data. If the wire angle, length of the tow line, and depth of the package are known, an offset can be calculated between the package and the vessel's position to provide accurate, updated fixes at those points where the actual measurements were collected.

3.5.2 Relocation Applications

Some instrumentation, designed to measure and record various physical parameters, can operate in an autonomous manner independent of surface support. These instruments are typically either positioned directly on the bottom or they are buoyantly suspended over a fixed anchor clump. Since boat traffic is a major consideration in many areas of Puget Sound, the simple expedient of attaching an identifiable surface float above an instrument package may not be a viable option.

For these applications, it is necessary to have the ability to accurately relocate the underwater package for data and/or equipment retrieval. Recording the surface position at the time of equipment deployment and release makes it possible for a vessel to return later to the approximate vicinity of the target's position. A relocation system can then be used to interrogate the target's transponder to supply the necessary range and bearing to the package. Some models can command the underwater package to either acoustically transmit recorded data or physically release a buoyed retrieval line.

3.5.3 Accuracy and Calibration

The associated equipment manuals should be referenced when conducting calibration checks. When in the field, an easy way of establishing positioning accuracy is to take reciprocal compass bearings on the same target. Approaching from different bearings on opposite sides of the compass should direct the recovery vessel to the same geographic point. Range accuracy can also be verified: When directly above the target package, the indicated range to the target's transponder should equal the bottom depth as shown on the ship's fathometer.

Since density variations within the water column have a direct relationship to acoustical signal velocities, it is important to know and adjust for the expected salinity concentration within the area of operation to minimize potential range error. Be aware that salinity concentrations can vary significantly in nearshore waters near sources of freshwater input (e.g., near the Duwamish River mouth, in Shilshole Bay, etc.).

4. MODERN GLOBAL POSITIONING SYSTEMS

Developed by the Department of Defense (DOD), the Global Positioning System (GPS) is a worldwide, satellite-based, radionavigation system consisting of a network of 24 operational Navstar satellites. The U.S. Air Force Space Command formally declared that the system was at "Full Operational Capability" in April, 1995 (USNO, 1996).

The DOD eventually requested that the Department of Transportation (DOT) oversee the process for making GPS available for civilian applications. In February, 1989, the U.S. Coast Guard (USCG) was assigned to develop a system for providing this access (Schlechte, *not dated*).

The present system is such that it can supply users with accurate three-dimensional position and time on a continuous basis anywhere on earth. Many GPS receivers are capable of providing the user with additional navigational parameters such as bearing-, distance-, and time-to-go estimates. The GPS's usefulness for all manner of terrestrial, aeronautical, and marine applications is growing rapidly. It is thought by many that GPS is well on its way to becoming the most universally-recognized positioning system-of-choice for fulfilling both navigational and surveying needs.

4.1 Standard Positioning Service (SPS)

The GPS provides two levels of service: (1) the Standard Positioning Service[9] (SPS) for use by the general public and (2) the Precise Positioning Service (PPS) which is restricted for use by the military under the DOD. The satellites transmit on two L-band frequencies: the SPS operates on the L1 frequency of 1575.42 MHz and the PPS operates on L2 at 1227.60 MHz (Dana, 1997).

4.2 Major Operational Elements of GPS

The GPS network consists of three major elements, commonly referred to as the Space, Control, and User segments (USNO, 1997).

4.2.1 Space Segment

The GPS utilizes 24 operational Navstar Block I, II, and IIA satellites, distributed in six orbital planes at a height of 20,200 km above the earth. This constellation provides users with between five and eight visible satellites anywhere on earth. Besides ranging information, the coded transmissions from each satellite contain its orbital and clock characteristics, system time, and status messages.

4.2.2 Control Segment

The Control Segment consists of one Master Control Station (MCS) in Colorado, five Monitor Stations, and three ground antennas distributed throughout the world. The Monitor Stations passively track all satellites, accumulating ranging data from each. These data are passed on to

[9] For the purposes of this document, only the SPS will be discussed herein as it is typically the only service available for non-military use.

the MCS where they are used to precisely compute[10] each satellite's orbit (ephemeris). This information, including clock corrections, is then transmitted up to the respective satellites as a way of updating their navigational messages to GPS users.

4.2.3 User Segment

The User Segment consists of all users and their associated GPS receiver-processors. These units receive the transmissions from all individual satellites that are currently in orbit above the horizon at that time. Each satellite continuously transmits the following kinds of data:

- *Pseudo-random noise (PRN) ranging codes.* These are used primarily for user positioning. They are the (1) course/acquisition (C/A) code, (2) precision (P) code, and (3) Y-code. (USNO, 1996)

- *Navigation message updates.* They contain precise orbital (ephemeris) and clock data. "Normally, a receiver gathers new ephemeris data each hour, but can use old data for up to four hours without much error." (Dana, 1997)

- *Almanac updates.* They contain the approximate, projected, orbital data parameters of all operational satellites. "Signal acquisition time on receiver start-up can be significantly aided by the availability of current almanacs." (Dana, 1997)

4.3 GPS System Time

Since user positions are trilaterated from satellite ranging signals, the time dimension is a critical component. Fortunately, GPS users do not require a precisely-timed clock as each satellite transmits time-of-arrival measurements along with its respective ranging data.

GPS system time is provided by its Composite Clock which also maintains the Monitor Station and satellite frequency standards. The Composite Clock is likewise referenced to the Master Clock at the U.S. Naval Observatory. The Master Clock also directs the Composite Clock to within one microsecond of Universal Time Coordinated (UTC). (USNO, 1997)

4.4 Sources of GPS Error

Positional accuracy can be compromised by the occurrence of any of a variety of potential sources of GPS error. These types of errors, and their subsequent loss in accuracy, are shown in the following table. (Dana, 1997)

[10] The reference coordinates of the MCS have been precisely surveyed with respect to the World Geodetic System 1984 (WGS-72). NOAA is responsible for maintaining satellite orbital accuracy (Haw, 1997b).

Sources of GPS Error

Type of Error	Description	Loss in Accuracy (in meters)
Receiver and PRN code noise	Internal electronic noise.	1
Selective Availability (SA)	Intentional SPS signal degradation.	When active, 30 increases to 100
Satellite clock errors	When uncorrected by the Control Segment.	1
Ephemeris data errors		1
Tropospheric delays	Changes in temperature, pressure, and humidity in lower atmosphere due to weather changes.	1
Unmodeled ionosphere delays	Transmitted model can only compensate for half of the time delay caused by ionization influences.	10
Multipath	Interference from reflected signals off surfaces near the receiver. (Hard to detect or avoid.)	0.5
Control Segment mistakes	Computer or human error.	1 m to 100s of km
User mistakes	Improper setups (e.g., incorrect geodetic datum).	1 m to 100s of m
Receiver errors	Software or hardware failures.	any size
Combined noise and bias errors	Satellite ranging errors.	15 per satellite

4.5 GPS Accuracy and Repeatability

4.5.1 Positional Accuracy

GPS accuracy, by itself, is generally better than 20 meters 95% of the time. However, for national security reasons, the DOD intentionally degrades SPS accuracy through the use of Selective Availability (SA) by manipulating the navigation message orbit data (epsilon) and/or satellite clock frequency (dither) (USNO, 1997). Eventually, this activity may no longer be a problem as, according to the Office of Science and Technology Policy National Security Council, "It is our intention to discontinue the use of GPS Selective Availability within a decade in a manner that allows adequate time and resources for our military forces to prepare fully for operations without SA."

When SA is in effect, the SPS has the following uncorrected[11] predictable 95% accuracies (Dana, 1997):

- 100 meters for horizontal
- 156 meters for vertical
- 340 nanoseconds for time

The level of positioning accuracy, or ranging error, can be evaluated at any given time by querying the GPS receiver status which should display the values of the four Geometric Dilution of Precision (GDOP) components. The GDOP reflects the overall quality of the geometric relationships of the satellites to the receiver in the form of range vector differences. (Dana, 1997)

[11] To increase absolute accuracy, initial GPS positioning data can be either post-processed at the end of an operation or differentially corrected while in the field to compensate for system errors.

The four GDOP components are:

- HDOP (Horizontal Dilution of Precision)
- VDOP (Vertical Dilution of Precision)
- TDOP (Time Dilution of Precision)
- PDOP (Position Dilution of Precision in 3D)[12]

The PDOP value is an indication of satellite geometry as it relates to the quality of a positional fix at that moment. In essence, the smaller the number, the better the satellite/receiver configuration. Values of 1 to 4 are generally considered to have excellent geometry, 4 to 6 are good, and 6 to 8 are fair (any values higher than eight will probably not meet acceptable accuracy criteria). Hypothetically, the geometric configuration of an upside-down pyramid, with a satellite occupying each of the four corners and the user's GPS receiver positioned at the apex, would yield a 'perfect' PDOP of 1 (McDuffie, 1996). A minimum of four satellites is required for a positional fix in 'true space'. Only three are required if the Z dimension (altitude) is already known at a comparable level of accuracy by the user. However, from a practical standpoint, no less than four should be used for positioning purposes on Puget Sound.

In a general sense, the above concept holds true for all triangulation and trilateration methodologies: as the LOP intersect angle becomes more acute between a target and its respective reference points, positional accuracy decreases. In other words, accuracy decreases as the baseline between any two reference points becomes shorter and/or the distance to the target increases.

Satellite elevation above the horizon is an important consideration as transmissions from low-elevation satellites must travel longer distances through the atmosphere, making them more susceptible to the introduction of noise from atmospheric disturbances. Transmissions from those satellites that are visible at elevations of 15^{o} or more above the horizon will typically be exposed to the least amount of atmospheric noise. However, there are many instances where satellites having elevations as low as 10^{o} above the horizon have provided suitable PDOP values. This is made possible because other receiver criteria had been met at the time, resulting in an acceptable geometric solution.

These criteria would include:

- the presence of additional numbers of useful satellites beyond the minimum four necessary,
- good spatial distribution of satellites, and
- atmospheric disturbances are minimal at the time.

Although visible satellite coverage is essentially continuous on the open waters of Puget Sound, there are times, especially in the more inland areas, when satellite transmissions may be blocked part of the time by geological features, tree canopies, manmade structures, etc. Under these

[12] The term 'PDOP' is also known as the Spherical DOP.

circumstances, it may be advantageous to first review the almanac or ephemeris file that covers the time frame for when a specific sampling event is to take place. The ephemeris file, which is automatically recorded by the users' receivers, contains the predicted orbital information three months in advance for all currently-active GPS satellites. Once downloaded to a PC, it can then be reviewed to determine which field days will be the most opportunistic with regard to maximum satellite exposure. This 'orbital preview' is a standard "pre-mission planning" task that is performed by EPA field personnel prior to the start of each field event.

The availability of from four to six high-altitude (15^o or above) satellites in a good geometric configuration (i.e., having a good spatial distribution as represented by diversified bearings between the target and the visible satellites) should provide sufficient accuracy for most water column and sediment sampling activities in Puget Sound, assuming that the GPS data are corrected for system error. The SPS level of service is designed to provide continuous, worldwide coverage at a PDOP value of six or less (USCG, 1998a).

As with LORAN-C, the Signal-to-Noise Ratio (SNR) is a good indicator of signal quality as it measures the strength of the incoming signal relative to background noise. Since accuracy is degraded as signal strength decreases, it is recommended that the SNR should not be less than 6.

Many makes and models of modern-day GPS receivers[13] have the option whereby the user can adjust various position filters, or masks. This is accomplished by setting minimum and maximum limits of acceptability for elevation, SNR, and PDOP. The result is that when these criteria are not met, the receiver stops computing GPS positions. Thus, a consistent level of precision can be maintained for all fixes logged during the course of a particular sampling event.

It is important to note that when the PDOP mask is raised, the receiver is then allowed to potentially log more positions during a specific time frame, but at the cost of reducing positioning accuracy. This is because as the masking criteria are set to less stringent limits, more of the lower-quality transmissions from other satellites are accepted into the positioning solution. The opposite is true when the PDOP mask is lowered. In the end, project-specific positioning criteria should be the final determining factor governing allowable positional accuracy.

4.5.2 Repeatability

Since GPS system accuracy is controlled at the federal level, the user has two available options for meeting project performance criteria:

1. Monitor receiver status (i.e., GDOP components) and operate only within the DOP limits that will meet project positional accuracy criteria.

2. Take redundant positional fixes at the same geographic point over a period of time for comparison purposes.

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[13] Survey results of the latest GPS receivers on the market are reported each January in the publication, GPS World, Advanstar Communications Inc., 859 Willamette St., Eugene, OR 97401-6806. They can also be found on the Internet: http://www.gpsworld.com/about/contact0.htm

> Redundancy can provide proof of the precision to which a measurement is made. In order for this proof to be meaningful, the inclusion of possible error sources must not be systematically duplicated in the redundant measurements. A well-understood example from terrestrial surveying is that, in an optically-read theodolite angle measurement, if all repeat angles were turned with the same horizontal circle reference set on the backsight, inaccuracy in that particular portion of the theodolite's circle would not be made apparent. Redundancy in a GPS survey is achieved primarily by way of a change in the relative geometry of the satellite constellation. . . . For GPS surveys, the geometry of the satellite constellation must be different for repeat station observations in order to eliminate potential sources for systematic errors due to multipath, orbit bias, and unmodeled, ionospheric, and tropospheric delay. Even if the repeat station observation is made on another day, data must be collected at a different sidereal time in order to obtain a different satellite configuration. . . . Redundant observations also provide the additional verification of centering errors and a second set of antenna height measurements. (Anderson, 1995)

With the first option, checking the GPS receiver status is relatively easy, especially on the more sophisticated models, and it has been pointed out in the previous section that the PDOP is a good overall indicator of system accuracy. In fact, it is good policy to record the PDOP value at each occupied sampling station as a way of documenting how well the project positioning criteria are being met. If the vessel's GPS system uses a monitor to graphically display its course, another method for estimating precision is to visually note the degree of 'chatter' within the vessel's track as its position is updated on the monitor.

The second option of occupying a known geographic point to determine absolute positional accuracy is a more complex issue. This is due primarily to the fact that with an ever-changing satellite constellation, absolute accuracy can only be established at that moment in time when the new geometric solution is calculated. Theoretically, this means that if positional fixes are updated at one-second intervals, the offset between the user's receiver and the fixed geographic point is also capable of changing second-by-second.

The best that can be hoped for then, is to conduct a horizontal control check by occupying a known reference point at periodic intervals throughout the course of a sampling event. As an example, the crew on Bio-Marine Enterprises's research vessel record their GPS position at a known point on their pier prior to their morning departure, then they take a second fix at the same point upon their return at the end of the day. An adaptation of this same strategy would be to conduct horizontal control checks at known points within the sampling area itself.

The EPA has written several excellent Standard Operating Procedures (SOPs) on the topics of GPS equipment preparation, field techniques, and data handling. Some of these documents may be referred to below for additional information:

- EPA, December 1996. Draft: *Data Collection Using Global Positioning Systems (GPS) Technology*. U.S. Environmental Protection Agency, Region 1, Boston, MA.

- EPA, January 1997. Draft: *Standard Operating Procedures for Using Region 5 Global Positioning System (GPS) Equipment.* U.S. Environmental Protection Agency, Region 5, Boston, MA.

- EPA, April 1998. *Standard Operating Procedures for Using the Global Positioning System (GPS) to Obtain Accurate Locational Data.* U.S. Environmental Protection Agency, Region 2, New York, NY.

4.6 Differential Data Correction

As shown in the preceding sections, there are many sources that can contribute to GPS data errors. The standard method for compensating for these errors is to differentially correct the raw GPS field data. The principle behind this differential correction process is to use the measured bias errors at a known reference point to correct or offset the bias errors at a specific user's location. These differential corrections may be applied in real-time while in the field, or at a later date through the use of post-processing techniques. Fixed geodetic points, known as reference or base stations, are established for the purpose of supplying differential correction data. The U.S. Coast Guard[14] currently maintains a comprehensive network of reference stations along both coasts of the United States. (Dana, 1997)

4.6.1 Real-time Differential

For waterborne sampling activities on Puget Sound where GPS is the primary navigational tool, the differential correction of the raw GPS field data in real-time is by far the most popular method for compensating for GPS error. Such a system is referred to as a Differential Global Positioning System, or DGPS.

4.6.1.1 Operational Description

During a sampling event, both the local USCG reference station and the user's GPS 'rover' receiver are acquiring the same satellite signals at any given moment (refer to Figure 6.). Unlike the roving receiver however, the reference receiver resides at a known geodetic point. The Coast Guard's reference receiver is thus able to calculate the errors of up to nine visible satellites in a specific area.

> Since the reference station knows where the satellites are supposed to be in space, and it knows exactly where it is, it can compute a theoretical distance between itself and each satellite. It divides that distance by the speed of light and gets a time. That's how long the signals should have taken to reach it. It compares that theoretical time with the time they actually took. Any difference is the error (or delay) in the satellite's signal. (Hurn, 1995)

[14] Frequent updates regarding GPS system status can be found in the 'U.S. Coast Guard Local Notice to Mariners' and in the 'CORS Electronic Newsletter'; both are put out by the National Geodetic Survey.

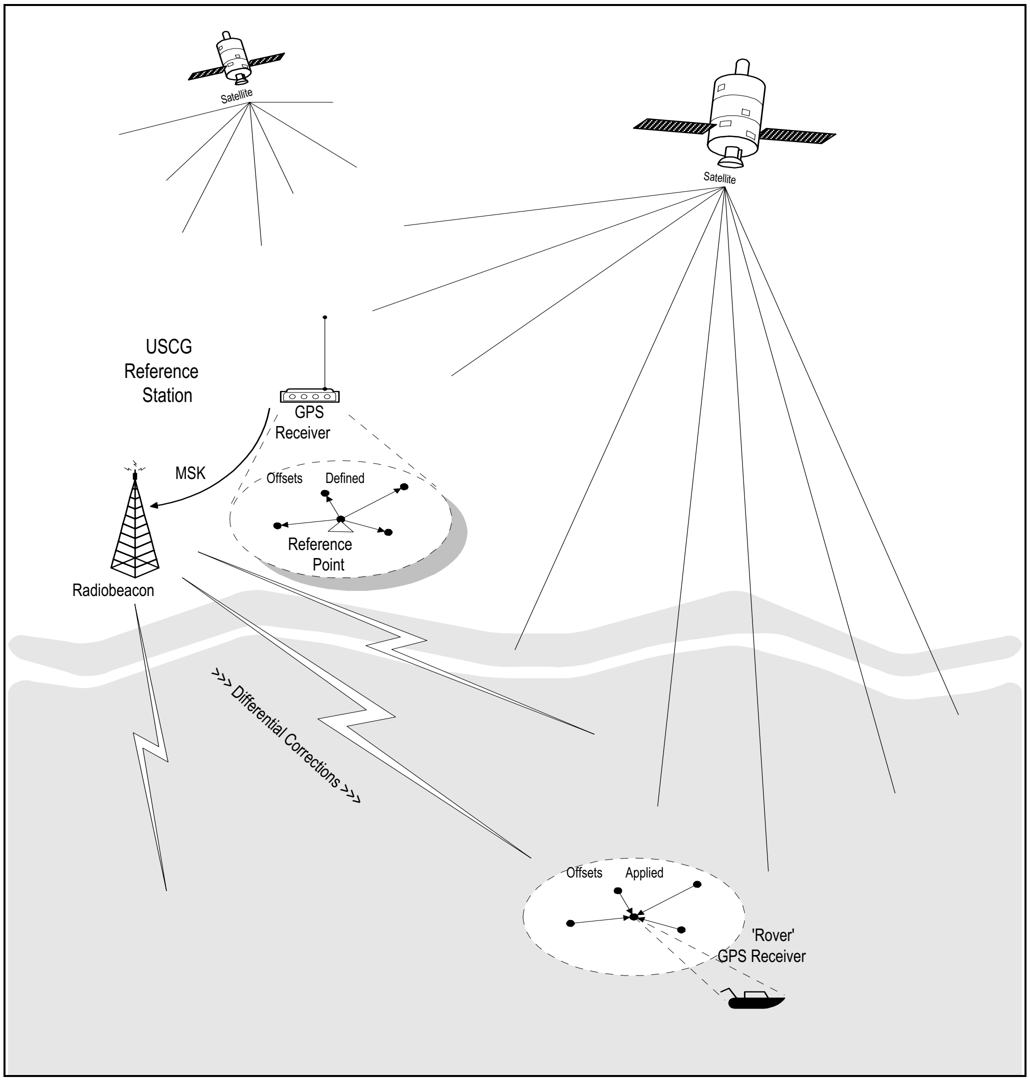

Figure 6. Differential (Real-Time) GPS Positioning

The resulting correction message, formatted to the RTCM SC-104 standard[15], is then transmitted to local users via an omnidirectional radiobeacon broadcast. Coast Guard radiobeacons are traditionally used to direct vessels that use Radio Direction Finding (RDF) equipment for navigation. This dual functionality is made possible by minutely shifting the frequency of a pre-existing radiobeacon signal up and down to produce binary strings of data. This type of frequency modulation is called Minimum Shift Keying (MSK). It has been shown that the MSK modulation technique has no adverse effect on RDF users.

The radiobeacon signals are usually transmitted every 20 seconds or less; the user's GPS receiver continuously applies these differential corrections to its own 'raw' satellite signals, thereby enhancing absolute accuracy as the bias errors are reduced.

[15] The RTCM SC-104 standard was established by the Special Committee 104 under the Radio Technical Commission for Maritime Services.

The USCG is mandated to meet the under-10 meter accuracy requirement for Harbor/Harbor Approach navigation, as defined in the Federal Radionavigation Plan. (It is quite common to experience a precision of ± 1 - 2 meters in Puget Sound.) DGPS performance is monitored at the West Coast Control Station in California.

The user can roughly calculate achievable accuracy by adding (Hall, *not dated*):

0.5 meters = reference station baseline error
1.5 meters = user receiver error
+ ## meters (add 1 m for every 150 km of separation between ref. station and user)
meters = total meters of expected error

Four USCG reference stations are presently located at various sites throughout the Northwest region. As shown in Figure 7., all four stations provide overlapping coverage within the Puget Sound area. When purchasing a differential receiver, it is recommended that it feature an 'automatic mode' setting which allows the receiver to automatically switch to whichever radiobeacon transmission is the strongest as the vessel travels from one area to the next.

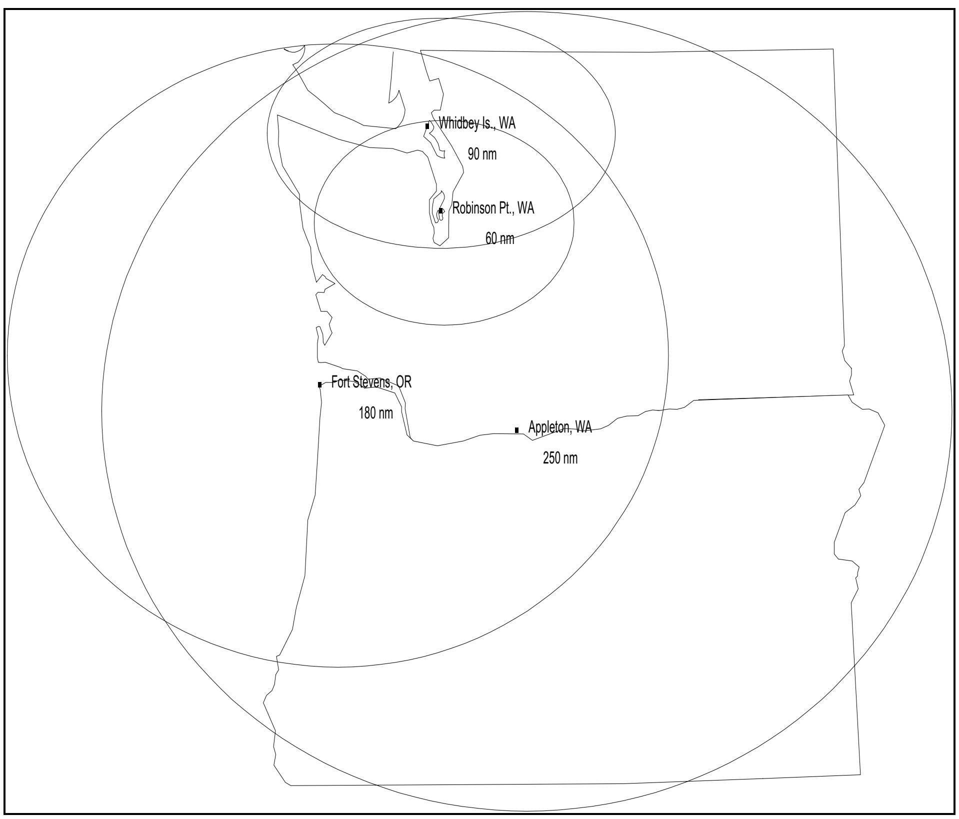

Figure 7. USCG Reference Stations with Nautical Mile Ranges
(USCG, 1997b)

The four regional USCG reference stations described above are listed in the following table (USCG, 1998b):

USCG Reference Stations, Northwest Region

Station	**Site Description**	**Frequency (KHz)**	**Field Strength (µV)**
Whidbey Is., WA	northwest end	302	75 at 90 nm
Robinson Pt., WA	east side of Maury Is.	323	100 at 60 nm
Fort Stevens, OR	Columbia River mouth, south side	287	75 at 180 nm
Appleton, WA	Washington/Oregon boundary	300	75 at 250 nm

Although the Coast Guard typically provides excellent differential coverage for users on Puget Sound, there may be some instances where a higher level of surveying precision is required, or where radiobeacon reception is poor due to interferences from geological formations or manmade structures adjacent to the operational area.

Under these circumstances, real-time differential correction can be supplied by setting up an individual base station at an unobstructed known reference point near the sampling area. This tactic should provide for interference-free reception while increasing positional accuracy. "Differential correction accuracy degrades as the distance between the base station and rover (user's receiver) increases. An estimate of this degradation is two ppm . . . for every kilometer between base and rover." Ideally, distance between the base station and the operational area should be within 300 miles (Trimble, 1996b). Base station receivers are quite expensive to purchase, but the rental option may be a cost-effective alternative for special project applications.

4.6.1.2 Strengths and Weaknesses

The strengths and weaknesses of DGPS for waterborne positioning applications include:

- data correction is automatic and immediately available
- a drifting vessel can readily re-acquire the active station with consistent accuracy
- the additional step of correcting data at a later date is eliminated
- the Coast Guard provides differential corrections at no cost to the user
- a high-end DGPS is relatively cost-effective to own ($5000 - $10,000 depending on options)
- at present, the Coast Guard differential network is not capable of supporting centimeter-level accuracy in real-time

For GPS users, real-time DGPS is used almost exclusively for scientific operations on Puget Sound. This is because the 2 to 25 meter accuracy range that is typically required on most marine projects is well within the capability of modern-day DGPS, and the advantages, as stated above, are numerous. In addition, the availability of the Coast Guard's overlapping differential coverage has significantly minimized the number and size of those open-water sectors where DGPS may not always be effective.

4.6.2 Post-processing

Differential post-processing is the means by which raw GPS data are corrected after the field event. This method is normally used when:

- the need to have access to corrected data while in the field does not warrant the additional expense of procuring a differential receiver and associated software,
- the differential transmissions from local-area reference stations are poor or intermittent, or
- when the collection of survey-quality (i.e., centimeter-level accuracy) data is a key requirement.

4.6.2.1 Operational Description

Before the raw GPS field data can be post-processed, certain requirements need to be met (Trimble, 1996b):

- accessibility to software for processing corrections[16]
- accessibility to base station files covering same time period and satellites as that used by rover receiver
- rover-to-base station distance of no more than 300 miles
- knowledge of base station position and antenna height
- base file continuously-logged intervals of no more than 30 seconds
- a compatible file format between both base and rover data files[17]

Several regional government agencies maintain base station files that are available at no cost to the public via a Bulletin Board Service (BBS) or the Internet (Hess, 1998). These sources would include:

- EPA, Region 10, Seattle
- U.S. Army Corps of Engineers, Seattle District
- Forest Service, Portland
- Portland State University
- King, Cowlitz, Thurston, Snohomish, and Skagit Counties

Base files can also be downloaded off the Internet at the Pacific Northwest Geodetic Array (PANGA) site. PANGA is a network of stationary GPS receivers, maintained by an international group of institutions including the University of Washington, that was created for the purpose of making seismic and volcanic risk assessments. Although only a half-dozen receivers are currently in place, there should be twelve instruments operating in Canada and seventeen in the northwest U.S. within two years. The base data is made available on-line for up to 10 days after generation. (PANGA, 1997)

[16] As an example, one data processing software package is marketed by Corvallis MicroTechnology, Inc., located on the Internet. Several GPS receiver brands (e.g., Trimble, Ashtech, Motorola, etc.) have processing software built in.
[17] The RINEX format can be used for those instances where data files are not compatable (Hess, 1998).

As another alternative, GPS base station files can be downloaded for a fee from one of the commercial providers of this service. A simple search on the Internet yields several sites that provide instruction and information regarding hardware and software options.

<u>4.6.2.2 Strengths and Weaknesses</u>

The strengths and weaknesses of the post-processing data correction method include:

- somewhat less cost and more compact than a DGPS[18],
- centimeter-level accuracy is achievable if a survey-quality GPS receiver is used,
- unlike DGPS, the post-processing step is an additional task that must be conducted before data are usable, and
- re-occupation of a pre-existing sampling point by the sampling vessel cannot be verified without the advantage of on-site differential correction.

4.7 The Future of GPS

It appears that the success of GPS in fulfilling its role as a primary positioning and surveying tool will insure its continued support to meet the needs of the various commercial, international, civil government, and national security interests. As the Senate Armed Services Committee points out, “It is clear that GPS offers the potential to revolutionize the movement of goods and people the world over. Civil and commercial exploitation of GPS could soon dwarf that of the Department of Defense and lead to large productivity gains and increased safety in all transportation sectors.” (USCG, 1997a)

4.7.1 Proposed Improvements

As DGPS technology continues to improve, it is hoped that advocates of this system will find an even broader range of application.

> Differential GPS has not often been associated with precise geodetic control work. Research and development are being conducted however, which could result in the viability of this technique, or some hybrid, for many applications, including perhaps geodetic control surveying. Differential GPS positioning does not attempt to solve the relative position between stations so much as it attempts to resolve the inherent errors in a single autonomous position. (Anderson, 1995)

As a DGPS system enhancement, one proposal that is being considered is to gradually convert the inland LORAN transmitter sites over to GPS base stations when LORAN-C is finally phased out. By doing so, this cost-effective measure could significantly improve real-time differential capabilities within the interior regions of the continental U.S. (McDuffie, 1998).

On another front, the Interagency Global Positioning System Executive Board (IGEB), with assistance from the U.S. Air Force, has plans to expand the civil navigational capabilities on future GPS satellites by adding a second, and possibly a third, civil frequency to the current GPS

[18] This is a moderate advantage as DGPS costs and equipment bulkiness are dropping rapidly every year.

L-band. This addition should significantly enhance system performance for both civil and military users. (Li, 1998)

4.7.2 GPS and GLONASS in Combination

While the U.S. has GPS, Russia has its own navigational satellite system which is known as the Russian Global Navigation Satellite System (GLONASS). The GLONASS Information Center in Moscow, which is operated by the Russian Space Forces, appears to have its share of ongoing, but intermittent, technical problems as it attempts to maintain a full satellite constellation.

As of the end of 1997, the GLONASS constellation consists of 16 active satellites out of a total of 24 individual orbits; the 8 remaining orbits are empty. January of 1996 was apparently the only period where all 24 satellites were on-line at the same time. Occasional signal anomalies, producing faulty measurements, continue to be observed from one or more of the satellites that remain operational. These anomalies can last from a half-hour to several hours, and the range errors can be anywhere from 100 meters to thousands of kilometers. Nevertheless, when GLONASS is working normally, its accuracy is about 7 to 10 meters 95% of the time. This is because, unlike GPS, the Russian military does not intentionally degrade system accuracy; GLONASS users do not have to contend with the Selective Availability issue. (MIT, 1997b)

Over recent years, a few receiver models have entered the market that are designed to simultaneously receive satellite transmissions from both the GPS and the GLONASS systems. The newest models have 24 channels, with 12 channels devoted to each system. The main advantage is that since these dual-system GPS/GLONASS receivers are able to access a greater number of satellites at one time, there is a potential for improvement in overall accuracy since a larger number of satellites are figured into the geometric solution.

> The principal benefit would be in the form of robustness of the combined system . . . (due to) the increased number of satellites in view. Even with a conservative assumption that GPS and GLONASS each would maintain a 21-satellite constellation, *all* users are assured of a minimum of 8 satellites in view above 7.5^{o} elevation angle; 99% of the users globally are assured of 10 satellites in view; and half the users would see 14 or more satellites. In single-receiver mode (i.e., without real-time differential applied), the position estimates obtained with GPS+GLONASS (combined) are significantly better than those from GPS (only), due entirely to the feature of Selective Availability (SA) in GPS. (MIT, 1997a)

However, when a dual-system receiver is using real-time differential corrections, accuracy is significantly *less* from that of a GPS-only receiver that is operating in the real-time mode.

> In (real-time) differential mode, the effect of SA in GPS is substantially neutralized and the measurements from the two systems can be treated as equals. The frequency diversity of the GLONASS signals, however, introduces calibration problems in receiver design in the form of signal path delays or inter-channel biases. These biases, if not calibrated out or accounted for, can be a source of significant error in differential mode, and may result in a net loss of accuracy. (MIT, 1997a)

In summary then, a dual-system receiver is capable of a higher degree of positional accuracy when real-time differential correction *is not* applied, but accuracy is noticeably less when real-time differential *is* applied. With the present-day GPS providing essentially 100% coverage in Puget Sound area waters, it is therefore suggested that a single-system GPS receiver with real-time differential capabilities be used for marine applications. Although a dual-system receiver would appear to be of questionable benefit, if any, under these circumstances, it has proven itself on more inland applications where there is a greater potential for signal interferences from tree canopies, canyon walls, etc.

It should also be noted that "the development of GLONASS appears to have slowed down considerably. After the steady progress of 1994 - 1995 that resulted in a full constellation of 24 satellites by January 1996, by September 1, 1997 the constellation had dwindled to 16 satellites. The last launch was in December 1995. All satellites from pre-1994 launches have been withdrawn, perhaps in preparation of new launches." (MIT, 1997a). It may be that because of these circumstances, there does not appear to be any obvious interest from the U.S. Government to make use of or help maintain this system. "Present needs and plans do not call for utilization of signals from GLONASS . . ." (Hall, *not dated*)

5. DATA COLLECTION AND RECORD-KEEPING

A proper set of field records should provide complete documentation with regard to both the intended and the actual scientific and positioning activities that take place during a sampling event.

5.1 Initial Project Description

Prior to the sampling event, all participating personnel should become familiar with the overall project scope and purpose, project sampling particulars, and station siting details. Ultimately, it is the project criteria that will govern the level of expected accuracy and precision of the selected positioning method. Planned station locating criteria and considerations should include,

- station coordinates,
- level of expected accuracy,
- siting particulars (i.e., spatial resolution, expected depths and currents, vessel traffic congestion, waterway constrictions, etc.),
- final coordinate data format (i.e., preference for datum, coordinate system, units, etc.), and
- contingency plans if navigational activities are compromised.

Awareness of project criteria may not be as big of an issue for the more routine sampling programs where samples are frequently collected the same way at the same stations by a small body of qualified personnel. However, a central reference source should always be available, should questions arise at any time (e.g., ability to contact project manager, project reference materials on board, etc.).

On the other hand, there are cases where a more formalized approach is required for documenting project directives. For instance, sediment sampling projects that fall under the Sediment Management Standards criteria are required to produce an initial Sampling and Analysis Plan. Among other things, this document must include full details with regard to station distribution and acquisition. As another example, the U.S. Army Corps of Engineers has stringent station positioning criteria which governs their actions during dredging and dumping activities.

5.2 Field Records

Station positioning documentation should be able to provide sufficient detail for determining:

- any significant horizontal differences between the vessel's surface position and the *in situ* measurement or sampling point,
- spatial offset between each prescribed and actual sampling point,
- relative spatial relationships between individual sampling points in a station array (i.e., station distribution),
- juxtaposition of a specific station array relative to prominent landmarks or other hard-point features,
- specific sampling points in such a way that another party would be able to readily re-occupy these same stations at a later date if necessary,

- type of activity that took place at each station,
- all sample and bottom depths at each station, and
- the time that a specific activity took place at each station.

In order to provide the kind of information listed above, the shipboard navigational record should include the following details:

- horizontal datum and coordinate system used,
- positioning method used,
- navigational equipment type, including how it was setup and used,
- significant changes in expected accuracy/precision (if using DGPS, note the PDOP value when logging a fix),
- calibration technique and associated data,
- any adverse weather or physical conditions that could affect expected accuracy,
- navigation personnel involved,
- identification of all reference points,
- raw and/or finalized navigational/coordinate data, including units of measurement,
- depth, local time, and type of activity (if sampling along a transect line, beginning and ending time, ship's heading, and any course changes should be included), and
- all changes/modifications to standard operating methods.

5.3 Coordinate Data Loggers and Shipboard Displays

At the most basic level, a set of coordinates are either plotted off of a nautical chart, read from a shipboard navigational device, or received from a shore-based survey party. The coordinates are then manually recorded in some type of navigational logbook. This method carries with it several distinct disadvantages, including:

- the potential for transcription errors, either during logbook entry or during transferal to another recording medium upon completion of the survey, and

- during a tracking exercise, the manual recording of coordinate data could prove to be very difficult due to the sheer volume involved.

Manual data entry and calculation errors would be minimized with a navigation system which has the ability to both calculate and electronically record final positional data in an acceptable format for easy uploading to a landside computer system at the end of the cruise. Many types of modern-day optical and microwave systems have electronic processing and recording capabilities in the form of electronic notebooks. Some Total Stations, when used in conjunction with a laptop PC and modem combination, can be remotely commanded to receive and transmit real-time data, initialize the taking of measurements, and select different measurement modes and functions.

As GPS is becoming an ever-more popular navigational tool, manufacturers are developing GPS receiver models that contain some very useful features. Some of the more sophisticated GPS receiver models have the ability to:

- graphically display an electronic scaleable navigational chart or GIS shape file of the area of interest, including the relative positions of pre-selected sampling stations (waypoints),
- log individual sampling points when actually occupied, or record all positions along a track line,
- import and export coordinate data in any of a number of acceptable formats, and
- provide real-time level of accuracy measurements.

The King County Environmental Laboratory uses Trimble Pro XL and Probeacon receivers interfaced with a laptop PC for Differential GPS positioning on its 45-foot research vessel. The PC graphically displays real-time vessel movement, all points and/or tracks where an activity took place, and all prescribed stations (waypoints). Included within the display are shoreline maps composed from GIS shape files created from digitized aerial survey photos and the associated NOAA bathymetry. Actual vessel-occupied positions are recorded as point, line, or area features. Both feature and waypoint files can be exported under a variety of GIS-compatible formats, including ASCII. When tied up at the Laboratory pier, positional accuracy typically averages about ± two feet.

5.4 Instrument Interfacing

5.4.1 Navigation and Sensor Data

Some marine activities such as hydrographic surveys require that a vessel collect data and/or samples while underway on a set course. For such tracking activities, the ability to electronically store other kinds of measurable data together with the navigational data under a common time element is a desirable feature. Under these circumstances, it is necessary that an electronic logging device be able to simultaneously record additional data from any of a variety of compatible acoustical sensors or *in situ* physical measurement probes along with the associated coordinate data.

Other projects might require that samples be collected in areas where GPS reception is either poor or non-existent, such as near large steel structures, within the vicinity of strong AM transmitters, or beneath piers. In these cases, a secondary distance-measuring device such as a laser range finder may be necessary to establish the horizontal offset between the exact sampling point and the closest viable GPS position. The primary positioning system would then need to be able to incorporate the offset data (both range and bearing) as a correction to the GPS data set.

5.4.2 Shipboard Instrumentation

Different shipboard instruments are sometimes interfaced together so that different types of navigational data can be viewed on a single readout display or so that one instrument can provide directional commands to another. For instance, depth data might be displayed along with ranging data on a radar screen or GPS data may be used to supply course-change commands to an autopilot.

In the past, combining data outputs from different makes and models of instrumentation has been difficult because of complications resulting from mismatched cabling and data formats. In an effort to enhance instrument compatibility, the National Marine Electronics Association developed Protocol 0183 (NMEA 0183). NMEA 0183 essentially sets the standard for compatible connector types and serial data formats between different manufacturers (McDuffie, 1998). It is recommended that all potentially interactive positioning and sensor instrumentation should be NMEA certified, if possible.

6. STATION KEEPING

Much of the professional-quality surveying and navigational instrumentation available today is potentially capable of accurately establishing geographic positions at distances significantly greater than that required for station positioning in most areas of Puget Sound. In practice however, vessel positioning accuracies may range from one-to-two meters to ten meters or more. This variation in accuracy is governed primarily by such factors as,

- degree of vessel maneuverability, as determined by hull size and design, including type and configuration of propulsion system,
- type of on-site activity involved,
- crew's level of knowledge and experience,
- equipment preparedness, and
- vessel response to external natural forces (e.g., wind, waves, and currents).

The added complication of having to accurately hold a vessel on station for the period it takes to perform the on-site work is perhaps one of the more significant differences between landside and waterborne surveying applications. The dynamic nature of the marine environment is such that a free-floating object is always subject to the influences of various natural forces unless corrective action is taken.

6.1 Drift Rate

Unless a vessel has some means of maintaining station position, its exposure to wind and tidal currents, both of which are almost always active in the Puget Sound area, will cause the vessel to eventually drift off site.

In Puget Sound, the prevailing wind and current activity is generally considered to be in a north/south orientation. Prevailing winds are typically out of the north during the summer months, and out of the south during the winter months. Due to the geological configuration of the Puget Sound basin, currents are primarily tide-driven rather than wind-driven.

When operating on the more open stretches of water, direction and rate of drift will usually be governed more by wind velocity, especially for shallow-draft vessels that have large sail areas (i.e., large superstructures for the wind to act upon). Near protruding headlands and in narrow channels, the higher tidal current velocities induced by these geological restrictions, especially during large tidal cycles, will have the greatest influence on vessel drift rate.

If instrumentation is deployed below the surface layer, a drifting vessel under control of surface forces may develop a wire angle with its submerged instrumentation. Wire angle is of concern because it can significantly effect sampling accuracy (refer to Figure 8). As shown in the illustration, as depth increases, the offset error between the vessel and the sampler will also increase under a set wire angle. This relationship is not linear, however, as resistance of the wire passing through the water column will give it the tendency to 'bow' outwards between the vessel and the weighted sampling device.

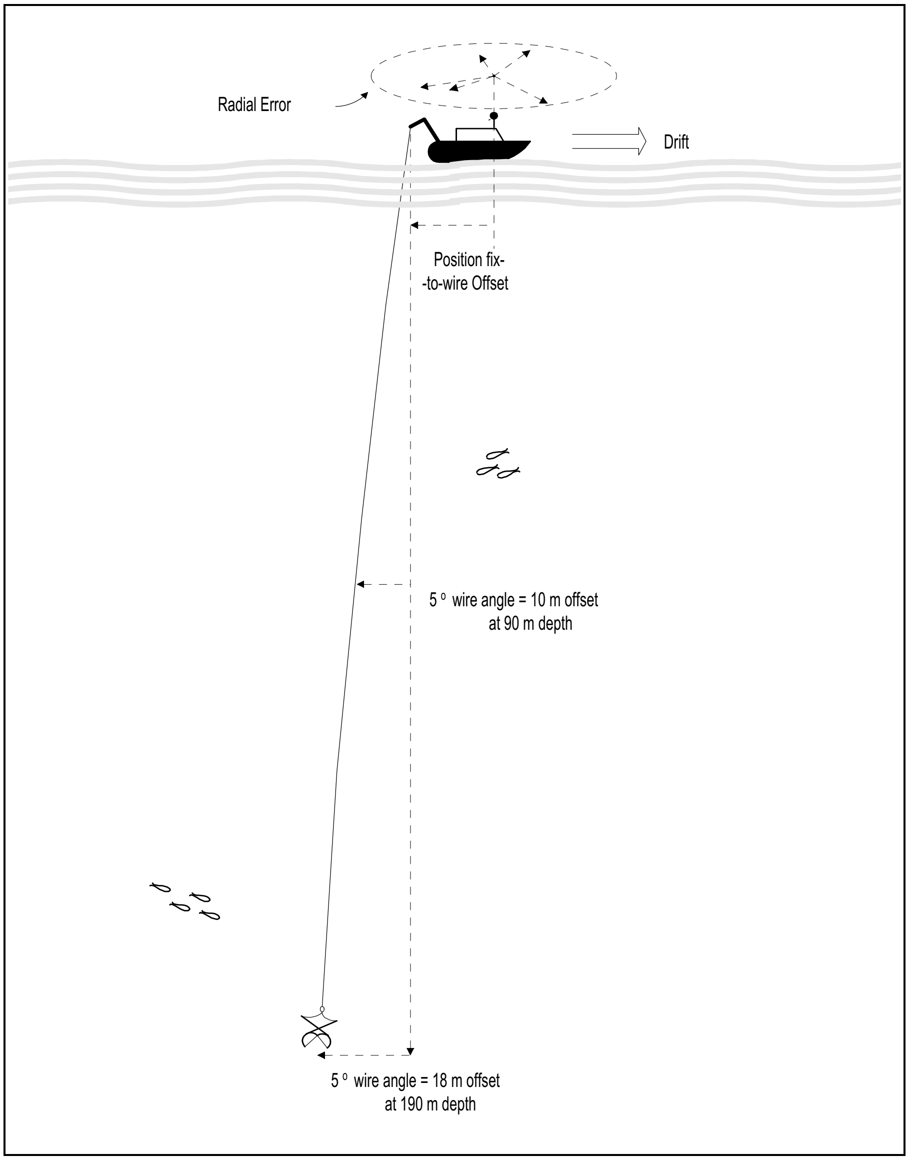

Figure 8. Effect of Drift Rate on Wire Angle

With any positioning method, overall positional error will include:

- the precision of the positioning method,
- the lateral offset between the hydrowire and that point on the vessel from which the position was determined, and
- the lateral offset between the hydrowire's attachment point to the vessel and the actual position of the sampling device.

Precision of the positioning method can be thought of as a radial error since there is a statistical possibility at any moment in time that positional error can be in the form of a spatial offset in any direction from that of the true positional point. This statement, however, does not hold true for the potential error offsets between the vessel's positional reference point and the hydrowire, and between the hydrowire and the sampler. These offsets are linear in nature since, for any given length of time, the vessel will hold onto a set bearing while wire angle orientation remains fixed.

It is recommended that wire angles should be kept under 5^{o} for all stationary sampling activities if at all possible. (Anything under 5^{o} will usually not be noticeable without the aid of a wire angle indicator.)

6.1.1 Corrective Measures

When not under power, all vessels will typically tend to swing perpendicular to the forces of wind (or current). As the vessel loses steerageway and falls off before the wind, pressure increases against the more exposed side of the bow relative to the opposite side. A state of equilibrium is eventually reached with the vessel abeam to the wind when the force vectors along the exposed side of the vessel become evenly distributed front to back on either side of the ship's pivotal axis.

From a positioning standpoint, a vessel might find it advantageous to utilize drift rate as a means of approaching a station from the upstream side. Care should be taken, however, when drifting on station while sediment sampling; core tubes could be pulled over or bent and descending grabs have a tendency to 'tumble' upon contact with the bottom under these circumstances.

The negative effects of drift rate diminish as water depth increases, since the vessel must travel a longer distance on the surface to pull the sampler out of alignment on the bottom. When sediment sampling on a sloping bottom in shallow water, the vessel should try to approach from the deep-water side; this reduces the likelihood of the grab tumbling against the up-slope side of the station. All positions should be marked at that moment when the vessel is directly over the station and the sampler first contacts the bottom.

6.2 Station Keeping Options

6.2.1 Hull and Propulsion Variations

There are many types of vessels that are used for environmental field activities in Puget Sound. Each design is different with regard to stability and station-holding capabilities. For the purposes of this discussion, there are two basic hull types: displacement hulls and planing hulls. A displacement hull, because of its mass, retains its stability in inclement weather and is slower to respond to wind and current influences. However, it has a relatively slow hull speed and its deeper draft prohibits it from sampling in shallow waters. A shallower-draft planning hull, on the other hand, may have a much higher cruising speed and is capable of operating in both deep and shallow waters, but platform stability and station-holding potential are readily impacted by increases in sea state and wind velocity.

The design of a vessel's propulsion system is another factor which can determine how efficiently a vessel can acquire and hold on a sampling station. Generally speaking, more propellers and/or thrusters mean more maneuverability options. It is a misconception, however, that all single-shaft vessels are less maneuverable than those having two; they usually just take longer to perform the same operation. As an example, a hull and propulsion configuration like that of a single-shaft harbor tug has good station-keeping potential due to the small hull length-to-beam ratio, high shaft torque, and large rudder size. On the other hand, a longer, narrow-beamed, twin-shafted vessel may find it difficult to turn within its own length, especially when exposed to high winds off the beam.

Those boats propelled by outboards and inboard-outdrives are usually quite maneuverable, as the directional thrust design is more efficient for this task than a fixed shaft/independent rudder combination. The addition of a bow thruster should increase maneuvering capacity to a certain degree, although its effectiveness is governed by hull length and horsepower rating.

6.2.2 Anchoring

Anchoring may be an option for some projects as it avoids having to continually maneuver to maintain station position. For example, when divers or equipment are on the bottom for an extended period while tethered to the surface support vessel, it is critical that the vessel remain stationary and have its propulsion system secured. However, the additional time it takes to weigh anchor to avoid a collision in a busy waterway could prohibit the use of this tactic.

The King County Environmental Laboratory often anchors their 45-foot research vessel by simply lowering a 700 pound anchor clump off the stern with minimum scope on the down line. In a busy waterway, the engines are often kept idling and out of gear. In an emergency, a diver could be quickly hauled up or sampling gear cut away. The anchor clump would then be immediately lifted clear of the bottom so that the vessel could maneuver out of the way of oncoming vessel traffic.

6.2.3 Marker Buoys

In nearshore waters where repeated sampling is necessary at the same location, anchoring a surface marker buoy above the sampling point may be a viable option. Doing so would then give the vessel the freedom to drift until the scientific party is ready to resample. The station can be conveniently re-acquired by visual means. It is important to remember that buoy scope can be influenced by current velocity, but buoy position can be verified by either the vessel's navigational system or an onshore survey crew at any time.

A modified halibut buoy is an excellent design for a marker buoy (refer to Figure 9.). The buoy anchor line can be made up from small diameter 600-pound test, braided nylon, halibut fishing leader. The bamboo pole is durable and fairly wind-resistant. It is also tall enough that the skipper can have an unobstructed view from the wheelhouse, especially if a brightly-colored flag is attached. The addition of a numbered plaque can help with identification if multiple buoys are deployed. Also, the ability to take radar ranges is made possible by mounting a radar reflector to the pole.

Ideally, the surface buoy should be positioned directly above its anchor to accurately mark a sampling point. This is usually not possible, however, as the ever-present currents will tend to force the buoy downstream. Unfortunately, this offset (buoy scope) does not remain constant; it will change over time as water depth changes during the course of a tidal cycle.

The solution is to pass the anchor line through a plastic ring that has been fixed tightly to the bottom of the pole below the lead ballast weight, as shown in the following figure. This free-hanging end of the anchor line is then tied to a one or two pound lead counter-weight. This counter-weight minimizes the scope and keeps it constant as water depth changes. (The anchor line must not be longer than twice the water depth expected.)

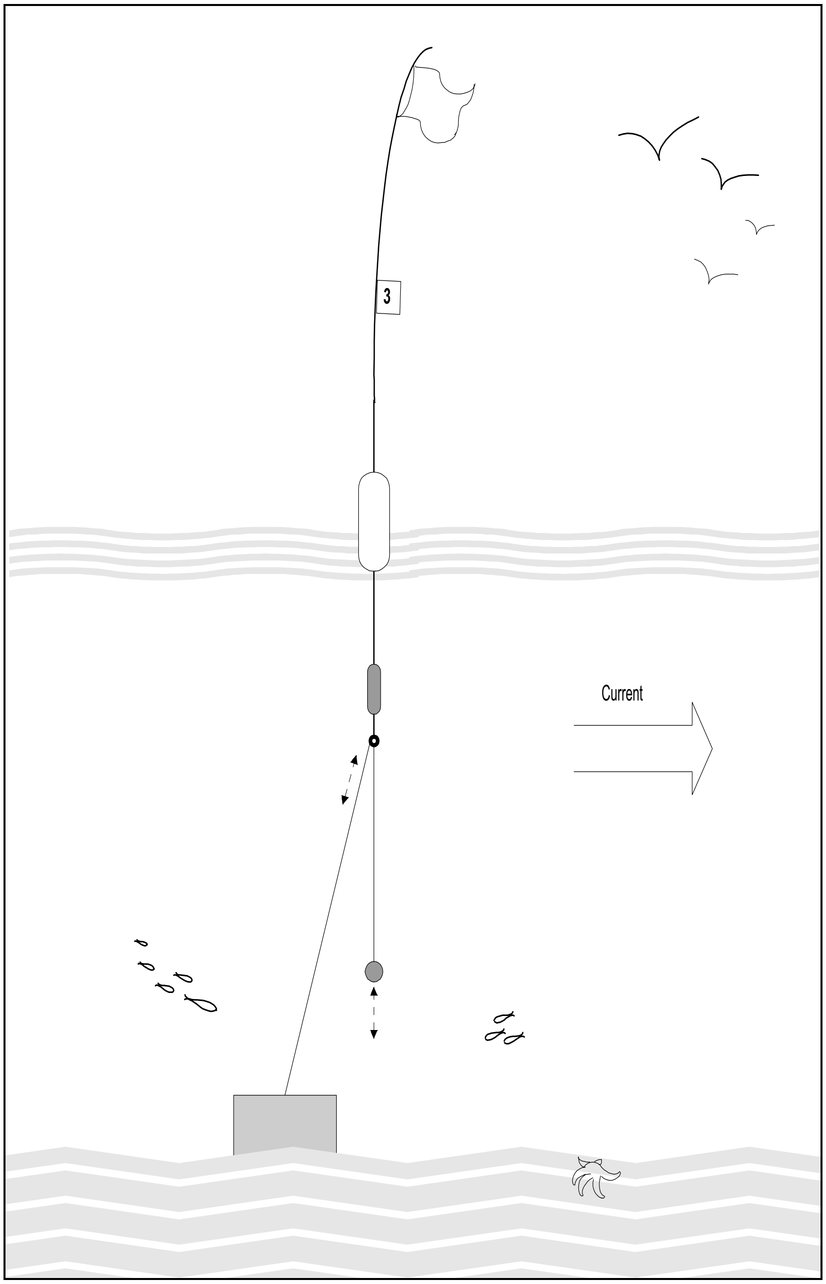

Figure 9. Halibut-Type Marker Buoy

7. REPORTING REQUIREMENTS

For several years, the Washington State Department of Ecology (DOE) and the former Puget Sound Water Quality Authority (PSWQA)[19] have been developing specific guidelines concerning the collection and analysis of marine samples. Environmental samples must be collected and analyzed in a standardized fashion so that:

- data from different public and private agencies can be equitably compiled or compared for consistent and objective evaluation,
- current analytical results can be related directly to historical results for trending purposes, and
- unbiased analytical results can be compared to current regulatory standards for a specific sample matrix.

Positional data resulting from these sampling activities must also be recorded and reported in a standardized manner. An agreed-upon universal format for such elements as datum, coordinate system, and units needs to be followed by the marine scientific community as a way of consistently identifying sampling points and areas within the Puget Sound region.

The EPA addressed the issue of standardized data reporting when it developed its information coding standards as part of its Locational Data Policy in 1991. Known as the Method, Accuracy, Description (MAD) codes, this coding system was designed to be used "for all environmental measurements collected by EPA employees, contractors, and grantees. A key premise of this policy is that secondary use of these data in Geographic Information Systems (GIS) and statistical mapping programs are significant to the overall mission of the Agency. To facilitate the integration of data into these systems it is important that coding of geographic coordinates and associated attributes be standardized." (EPA, 1995)

7.1 Navigational Data Standards

7.1.1 Datum and Coordinate Systems

Cartographers define a datum as a mathematical model of the Earth that relates to a specific planetary reference point such as the center of the Earth or the Earth's center of mass. Such a model is needed because it is not possible to represent the spheroidal Earth as a two-dimensional flat surface without distortion. The shape of the Earth is really that of an ellipsoid, as centrifugal force has deformed the spherical shape outwards along the equatorial axis.

". . . the ellipsoid which provides the best fit for the Earth's geoid[20] for North American Datum 1983 (NAD 83) is the GRS-80 ellipsoid." (Petrillo, 1998) The datum which incorporates this particular ellipsoid is referred to as the World Geodetic System 1984 (WGS-84). For the hydrographic surveyor, NAD-83 is essentially equivalent to WGS-84. Over the next few years, maps published by the U.S. Geological Survey will use NAD-83. (Trimble, 1996a)

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[19] The PSWQA has since been replaced by the Puget Sound Water Quality Action Team (PSWQAT).

[20] "A geoid is a representation of the surface of the Earth over which the Earth's gravity is constant." (Trimble, 1996)

Although a datum must always be based on a specific planetary reference point, it cannot by itself identify geographical points on the Earth. Some type of coordinate system such as lat/long is therefore required. A coordinate system is essentially an organized and systematic series of intersecting identifiable lines whose intersections are typically used to describe a point in either two- or three-dimensional space. Unlike a datum, a coordinate system does not require a planetary reference point. Instead, it usually relates back to some artificial reference point (e.g., longitude can be referenced back to the prime meridian in Greenwich, England, while a given State Plane system is always referenced back to its respective, artificial point of origin). Algorithms, known as map projections, are used to convert between lat/long coordinates and various linear northing/easting grid systems.

Several regional government agencies have now standardized their coordinate system/datum formats. For instance, the King County Environmental Laboratory has standardized all of its coordinate data to Washington State Plane under the NAD 83 datum. In 1995, the U.S. Army Corps of Engineers, as part of its Dredged Material Management Program (DMMP), also standardized its coordinate data format:

> Sampling location data will be entered into the Dredged Analysis Information System (DAIS) in the form of latitudes and longitudes referenced to North American Datum of 1983 (NAD 83) which is considered equivalent to the World Geodetic System 1984 (WGS 84). If sampling locations are referenced to a local coordinate grid, the local grid should be tied to NAD to allow conversion to latitudes and longitudes. Latitudes and longitudes referenced to the North American Datum of 1927 (NAD 27) can easily be transformed to NAD 83 (DMMO, 1995).

As a result, it is therefore recommended that all horizontal coordinate data generated by the marine scientific community within the Puget Sound region should be presented in either the latitude/longitude or the Washington State Plane coordinate system under the North American Datum of 1983 (NAD 83). If another local coordinate system is used, it should be identified and its relationship to the NAD 83 National coordinate system should be clearly defined (FGDC, 1996).

7.1.2 Horizontal Accuracy

Unlike landside surveying and mapping activities where precise position identification is a primary end product, sampling activities in Puget Sound typically place positioning data in more of a supportive role to that of the actual sample collection and analysis activities. Ideally, positioning data accuracies, as with laboratory analytical accuracies, would have standardized definable limits for all marine sampling activities. Unfortunately, such is not the case because:

- it is quite difficult to guarantee consistently ‘tight’ surface positioning accuracies for all occasions when operating within a dynamic fluid medium under all weather conditions,
- most field groups do not have the means to determine precisely the geographic locations of underwater sampling points, and
- currently, there is no single standardized equipment type or navigational method that is used universally by all research vessels operating in Puget Sound.

A number of committees, such as the Federal Geographic Data Committee (FGDC), have been created with the intent of addressing the various issues surrounding geospatial accuracy standards for specific water-based activities. The following is an excerpt from a 1996 FGDC draft document:

> Part 5, NAVIGATION CHARTS AND HYDROGRAPHIC SURVEYS. This part will specify minimum standards for hydrographic surveys so that hydrographic data are sufficiently accurate and spatial uncertainty is adequately quantified for safe use by mariners. It will provide a common framework to evaluate and assess hydrographic data for a range of applications through a standard statistical approach. This part will be based on the recently revised International Hydrographic Organization (IHO) Standard for Hydrographic Surveys, which is in the final stages of review by the international community. Potential users . . . are agencies that conduct surveys of the marine waters, including the high seas, coastal and estuarine waters, and inland lakes and rivers. The lead agency is the Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service. The responsible FGDC subcommittee is the Bathymetric and Nautical Chart Subcommittee (FGDC, 1996).

Rather than recommending a set level of horizontal accuracy, the National Standard for Spatial Data Accuracy (NSSDA) has suggested that “ultimately, data users must identify acceptable accuracies for their applications. Data and map producers must determine what accuracy exists or is achievable for their data.” (FGDC, 1996). In concurrence with this thinking, it is suggested that project-specific criteria should ultimately define the level of expected positional accuracy of the various environmental activities taking place within the Puget Sound region.

In addition, “the producer of the spatial data will determine the geographic extent of data to be tested and the amount of testing.” The FGDC’s suggested method for testing is to “test horizontal accuracy by comparing the planimetric coordinates of well-defined ground points with coordinates of the same points from an independent source of higher accuracy.”

The FGDC also recommended that the horizontal reporting standard should be “the radius of a circle of uncertainty, such that the true or theoretical location of the point falls within that circle 95 percent of the time.” The vertical reporting standard should be “a linear uncertainty value, such that the true or theoretical location of the point falls within +/- of that linear uncertainty value 95 percent of the time.”

7.1.2.1 Regulatory Guidelines

Some government agencies have elected to develop their own accuracy standards. As an example, the Dredged Material Management Program (DMMP), developed by the Army Corps of Engineers, contains specific positional accuracy guidance as follows:

> A precision navigation system should be used to record all sediment sampling locations to a geodetic accuracy of $\pm$ 2 meters. In addition, all samples should be obtained as close as possible to the target locations provided in the project sampling plan. Such accuracy can be obtained with a range of positional hardware such as microwave trisponders, differential GPS, electronic measuring devices, etc. The exact positioning system to be used and

associated QA/QC procedures should be documented in the project sampling plan (DMMO, 1995).

Before implementing a new sampling program for regulatory purposes, it is important to be aware if project-specific accuracy standards have been formally identified by the local regulatory agency. This is true even if the proposed project does not fall into the regulatory category; the ensuing data results may eventually be integrated along with other sampling entities within a regulatory agency's database, in which case overall consistent positional accuracy would be critical.

The following table lists a few of the more prevalent positional accuracy standards as recognized by some of the local government agencies.

Government Agency Positional Accuracy Standards

Agency	**Sampling Area/Type**	**Expected Accuracy[21]**	**Document Reference**
EPA (Locational Data Policy)	overall	± 25 meters	(EPA, 1992)
EPA: Region 2	overall	± 5 meters	(EPA, 1998)
Washington State DOE	marine sediments	± 3 meters	(DOE, 1995)
Army Corps of Engineers	marine sediments	± 2 meters	(DMMO, 1995)
King County	marine sediments	± 1 - 2 meters	(KCEL, 1997)

7.1.3 Vertical Accuracy

For landside surveying operations the accepted standard is to report the vertical measurements as height above the ellipsoid (HAE). However, for waterborne positioning applications on Puget Sound, it is a preferred practice for many groups to report height as water depth adjusted to mean lower-low water (MLLW). Barring that, sampling and bottom depth data could be reported in any format as long as it is always accompanied by unit of measurement, date, local time, and vertical reference point (e.g., keel depth, surface depth, relative to a specific altitude, etc.).

With most marine positioning activities, the vertical dimension is of secondary importance when establishing spatial placement. That, coupled with the fact that the typical GPS navigational system calculates the vertical dimension with significantly less accuracy than it does the horizontal, lends itself to the suggestion that another type of instrument such as a good-quality fathometer should be used as the norm for providing this vertical component.

7.1.4 Time of Occurrence

Date and time should always be recorded for each specific sampling and data collection activity during an operational event. It is suggested that for the Puget Sound region, local time should be used rather than UTC. It should be in the 24-hour format (to allow for computerized sorting) and should be recorded in either Pacific Standard or Daylight Savings Time, whichever is in effect at

[21] Project-specific applications may require different accuracy criteria.

the time of the sampling event. This practice should hopefully reduce the likelihood of date and time errors when consolidating or comparing data between different operational groups.

7.1.5 Coordinate Conversion Programs

It is not necessary to record initial positioning data in the final reporting format as different coordinate transformation programs are now available for readily converting between different datum/coordinate systems.

CORPSCON is a popular MS DOS-based conversion program that can be downloaded for free from its respective Internet site. CORPSCON was created by the U.S. Army Topographic Engineering Center for the purposes of doing coordinate convertions between geographic (i.e., lat/long), State Plane, and Universal Transverse (UTM) in NAD 27 or NAD 83 (CORPSCON, 1998). If desired, range/azimuth polar coordinates can also be converted to one of the above grid-coordinate systems (Droker, 1997).

As a second option, ‘Geographic Calculator’ is a comparable conversion software package that can be purchased from Blue Marble Geographics[22] for about $400. According to the vendor, “The Geographic Calculator enables interactive and batch transformations of coordinates from virtually any coordinate system to any other. You can transform between coordinate systems, calculate the distance and azimuth between two coordinates, and calculate the coordinate position at a known distance and azimuth from a known coordinate. The Geographic Calculator also computes grid convergence, point scale factor, datum shifts, and grid shifts.” (Geographic Calculator, 1998).

[22] Blue Marble Geographics, 261 Water Street, Gardiner, Maine 04345 U.S.A. Sales: 1-800-616-2725.

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